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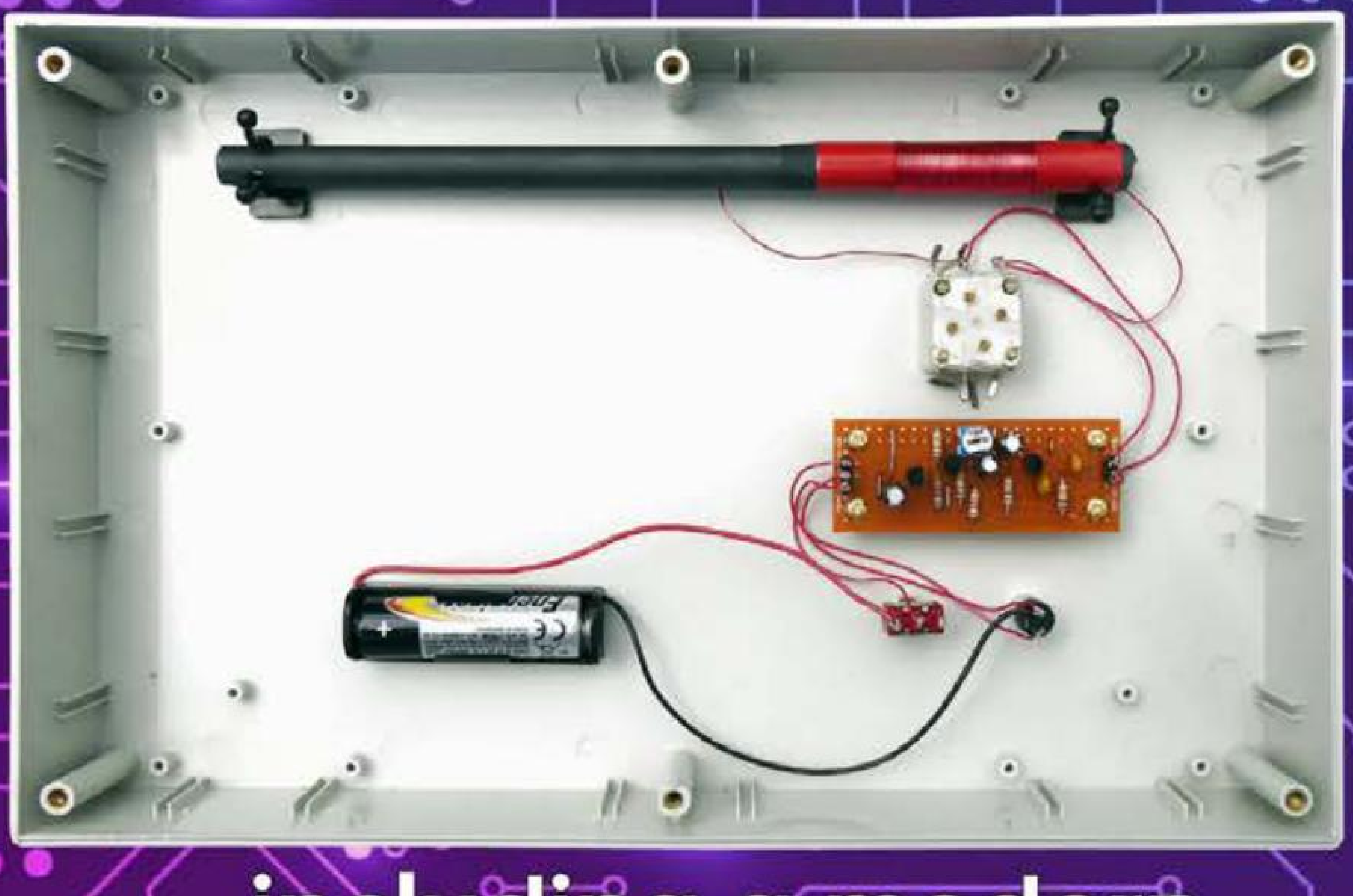
Measuring frequency response with a PC sound card, part 2

Audio Out
An instrument fuzz box with germanium transistors

3D Printer Filament Dryer
Putting it together

Teach-In 12: a new series on radio technology!



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Capacitor Discharger

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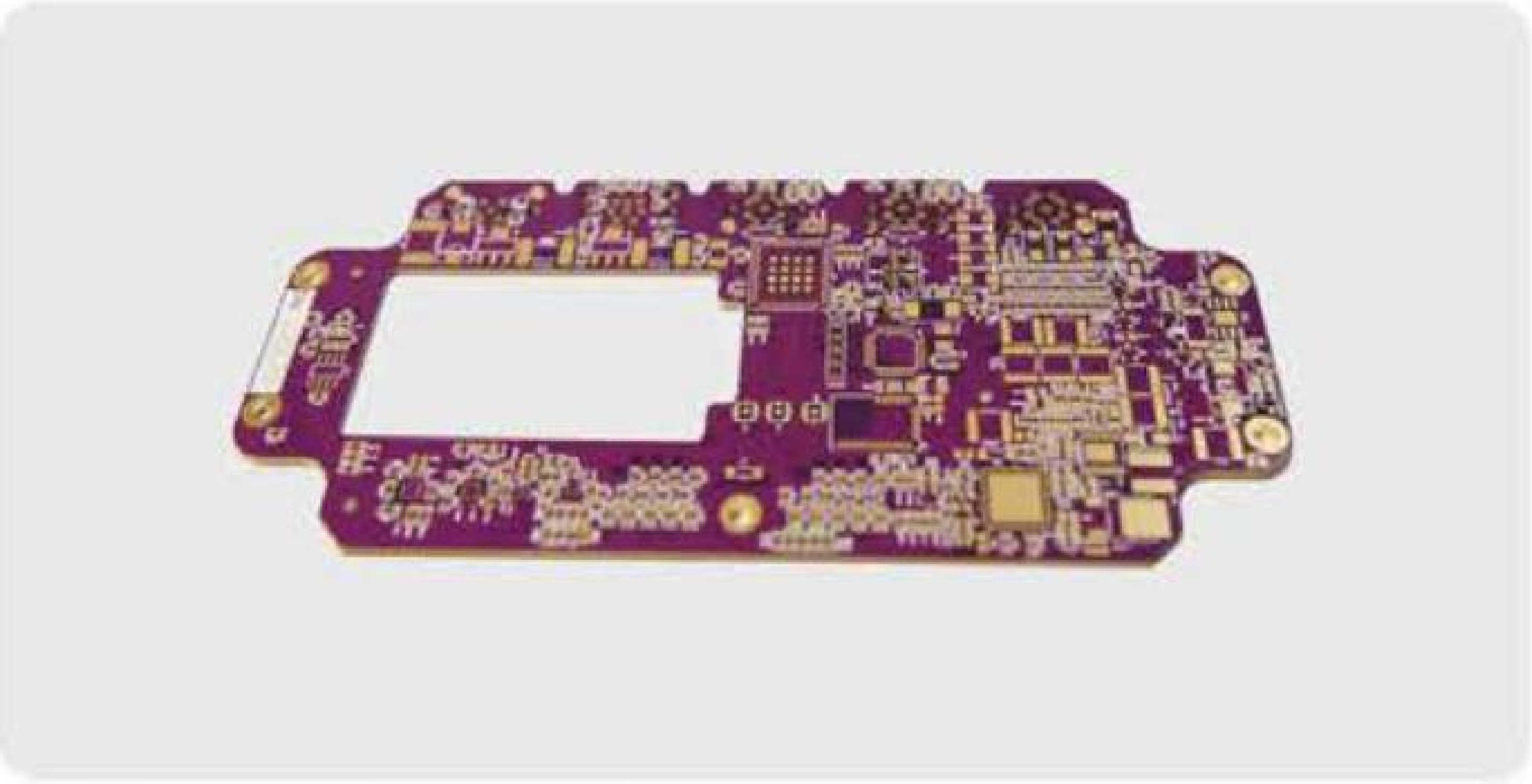

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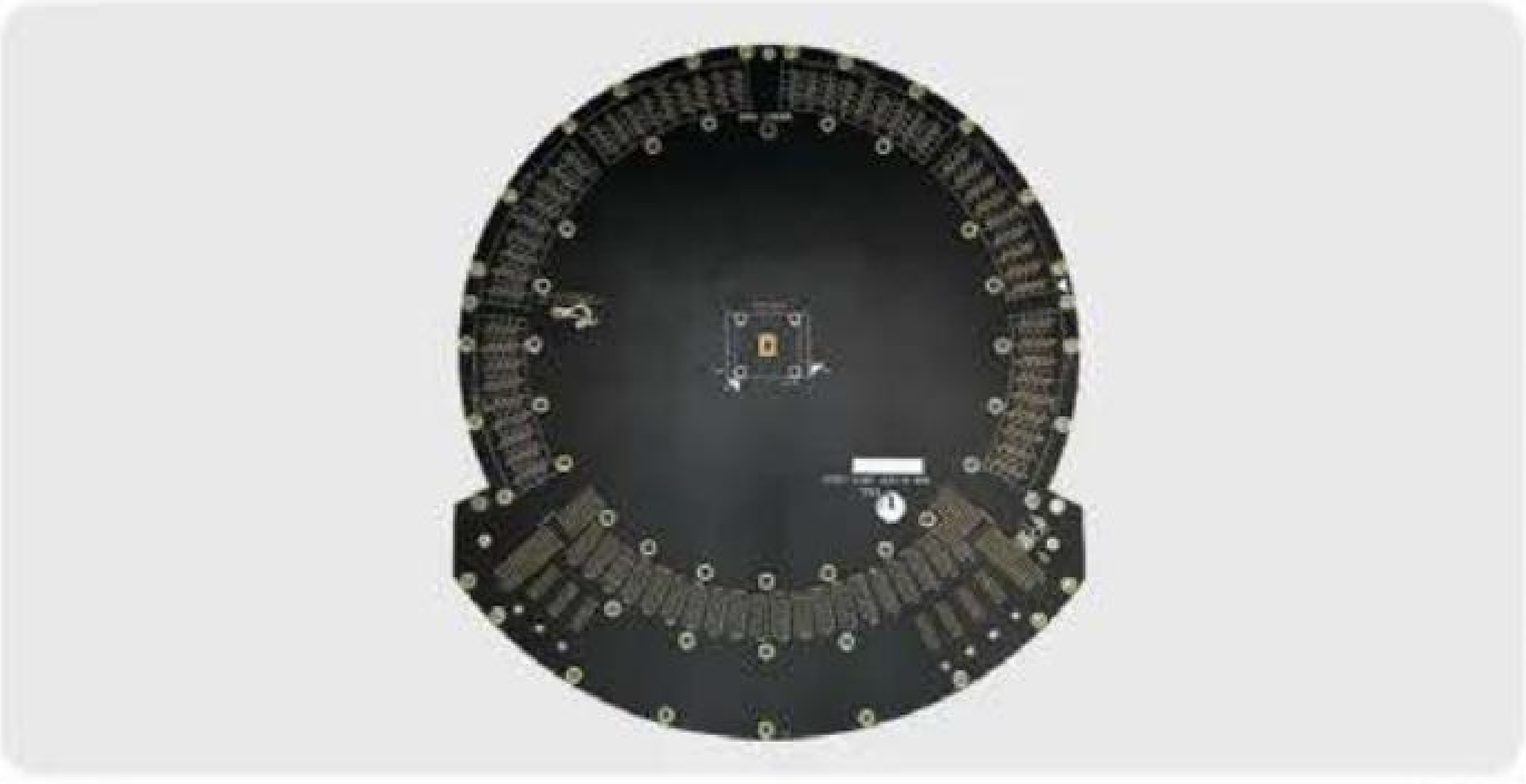

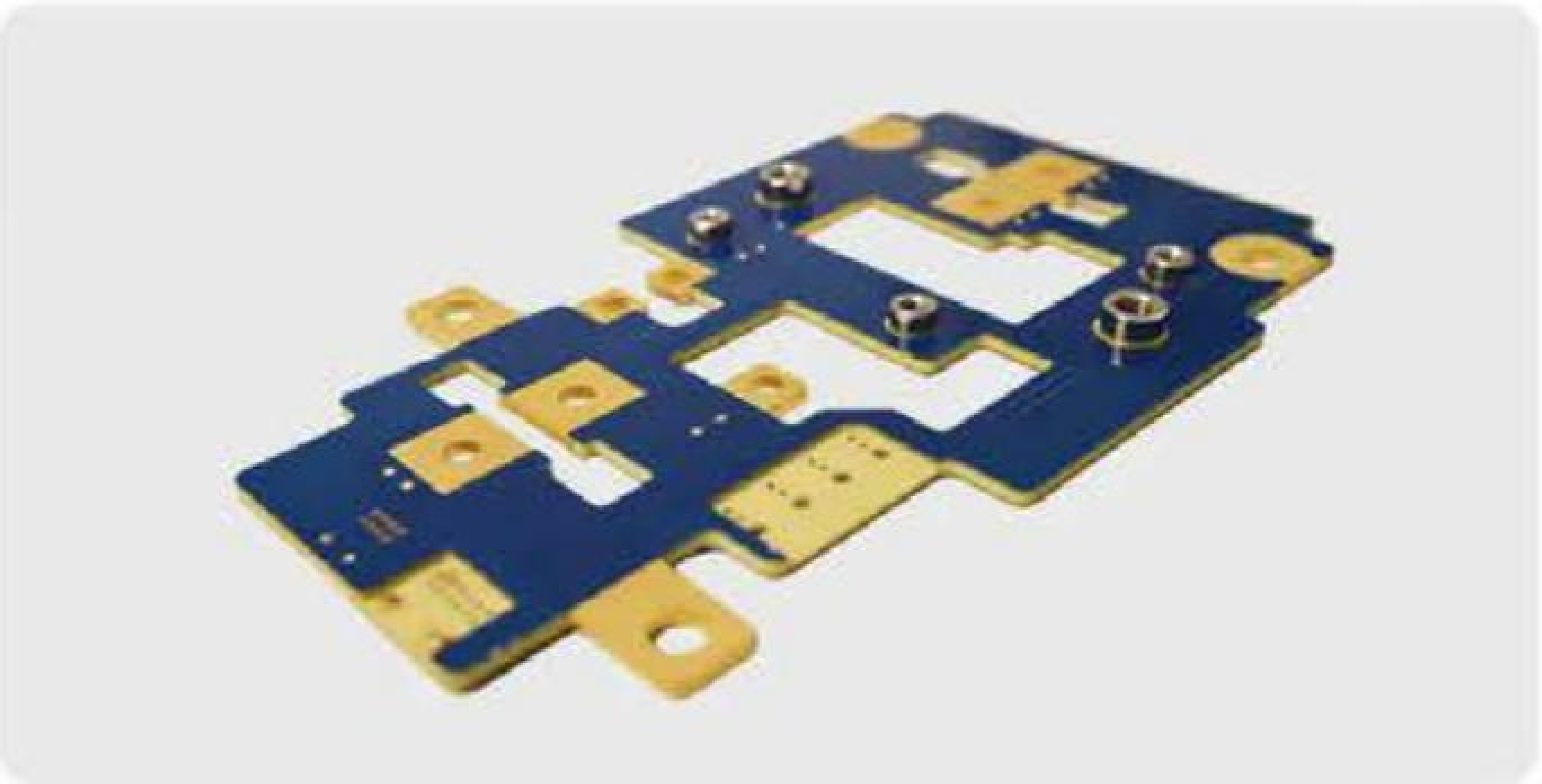

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November 2025
ISSN 2632 573X

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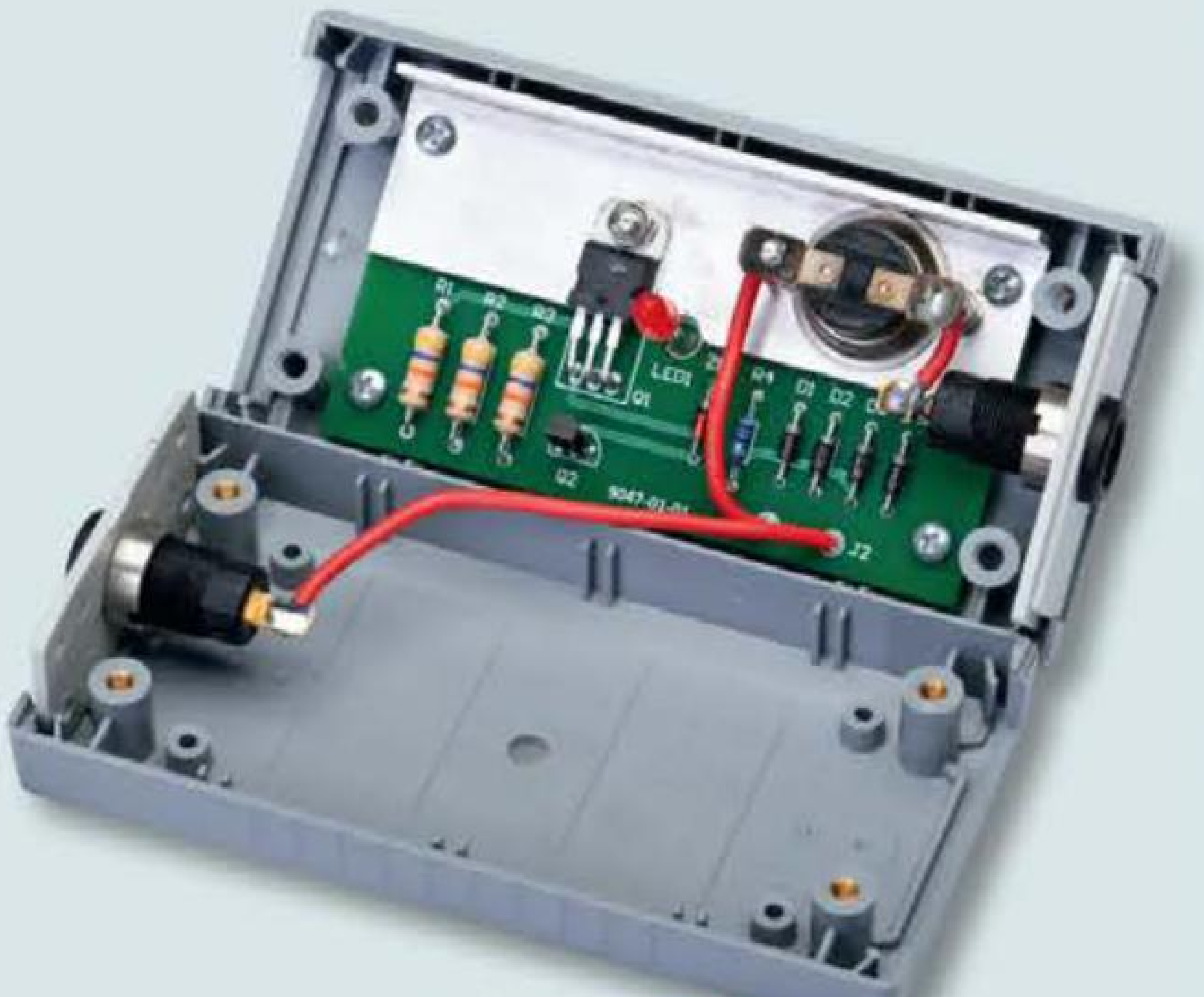

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Isolation: 420VAC ±600 VDC
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Read everywhere.

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The December 2025 issue of *Practical Electronics* will be published on Wednesday, 5th of November, 2025 (see p80).

Renewals paid by PayPal, Visa and Mastercard are now handled via our website:
www.electronpublishing.com

Practical Electronics

Volume 54. No. 11
November 2025
ISSN 2632 573X

Editorial

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Questions about articles or projects should be sent to the editor by email: pe@pemag.au

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Some projects and circuits published in *Practical Electronics* employ voltages that can be lethal. Do not build, test, modify or fix any mains-powered equipment unless you fully understand the safety aspects involved and you use an RCD (GFCI) adaptor.

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Many SSDs have a limited lifespan no matter what

There's a myth that's been floating around for a while: solid-state drives (SSDs) are more reliable than mechanical hard drives because they don't have moving parts. At first glance, it makes sense. Things that spin or slide will wear and eventually fail. But "no moving parts" doesn't mean "lasts forever".

Mechanical hard drives are, in many ways, miracles of engineering. They spin at 7200 RPM day and night for years on end, with the heads flying just above the surface of the platters while they read and write data. In my experience, if you keep them cool and don't knock them about, they often last decades. Sure, one fails every now and then, but it's rarer than many people think.

In contrast, I've had much worse luck with SSDs. They start out wonderfully fast – handling gigabytes per second when new – but over time, their performance can fall away. Sometimes, they simply fail without warning, which has happened to me a couple of times.

A few years ago, we replaced some trusty old mechanical drives with three Western Digital Green SSDs in a RAID5 array. These held our magazine layouts, product photos and other day-to-day files.

For the first few years, everything seemed fine. Then I noticed that instead of handling the hundreds of megabytes per second you'd expect, the throughput had collapsed to less than 10MB/s. That's worse than an old mechanical drive from the 1990s!

Testing each SSD individually showed the same thing. I replaced them with newer, higher-end SSDs and performance immediately returned to normal. The old ones, meanwhile, were too slow even for backups. I gave up after trying to copy a few hundred gigabytes; two days later it was still crawling along, barely 20% done. After only 4½ years of light use, all three SSDs were basically unusable.

Why does this happen? NAND flash has a limited number of write/erase cycles, typically a few thousand for consumer-grade TLC or QLC flash. Controllers use wear-levelling to spread the writes evenly, but the cheaper the drive, the less margin you have before cells wear out. Once that happens, performance falls off a cliff. And unlike hard drives, which often give some warning as bad sectors multiply or the bearings get noisy, SSDs can just stop dead.

So while it's tempting to think that "solid state" means "permanent", the reality is different. SSDs are quieter, cooler and much faster than mechanical drives, but they're not invincible. Don't assume an SSD will last forever. Buy good ones and always keep backups. Spinning or not, no storage medium lasts forever.

Nicholas Vinen, Electron Publishing (Australia)*
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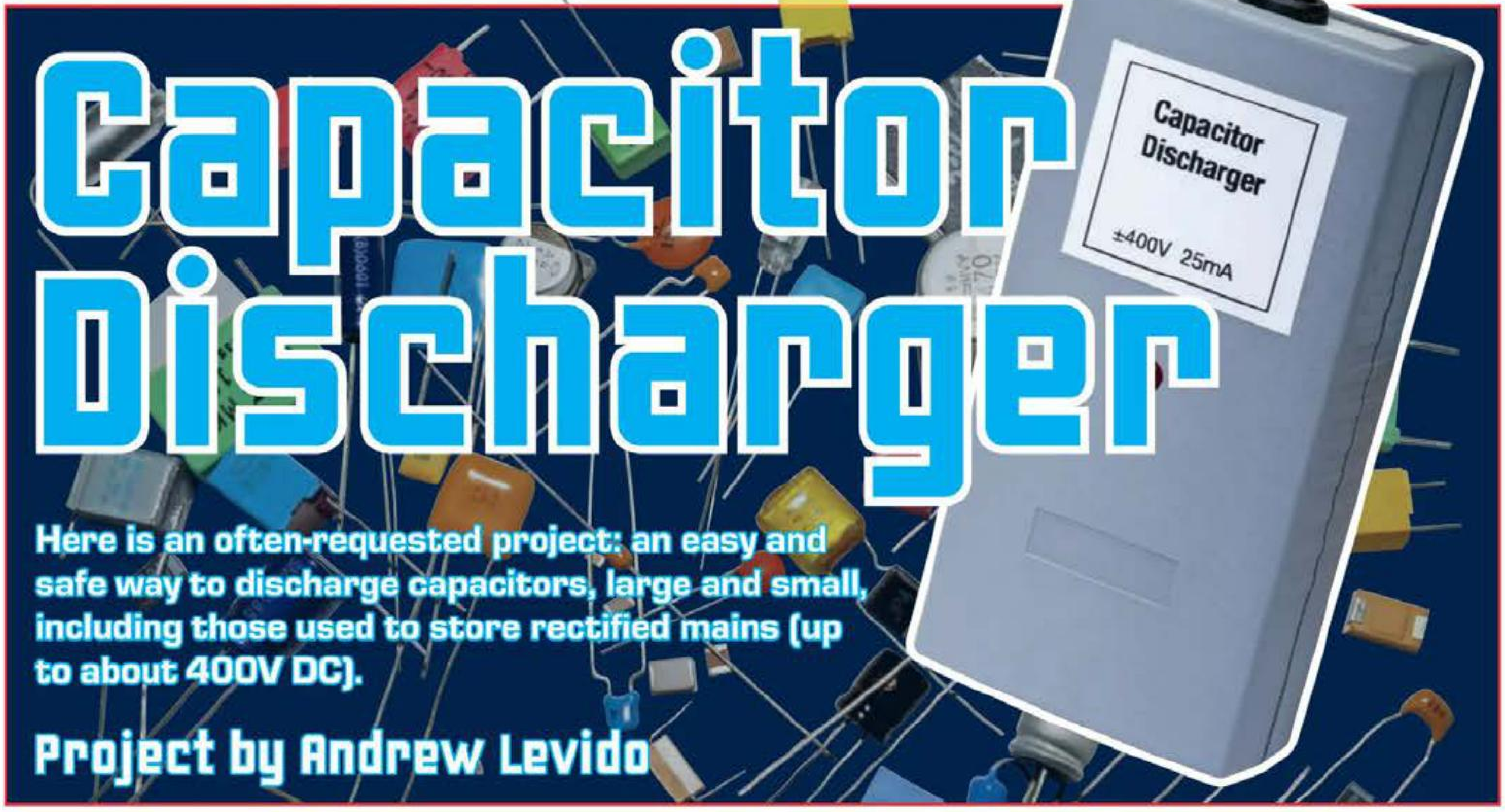


Capacitor Discharger

Here is an often-requested project: an easy and safe way to discharge capacitors, large and small, including those used to store rectified mains (up to about 400V DC).

Project by Andrew Levido

If you have ever worked on high-power audio amplifiers, vintage radios or switch-mode power supplies, you have probably been 'bitten' by a capacitor that remained charged after the circuit was disconnected from the power source.

Even if you have been careful to keep your fingers out of the way, it is all too easy to accidentally discharge such a capacitor with a soldering iron or screwdriver, with startling and perhaps damaging consequences.

It is therefore always good practice to safely discharge such capacitors before working on a device. You should definitely not do this by shorting the capacitor with a test lead (or worse, a screwdriver), since the amount of energy stored can be significant and the peak currents could be huge.

Doing so is not good for the capacitors, the printed circuit board (PCB), the shorting device or the nerves of anyone nearby.

It's much better to use a controlled discharge device that limits the current to an acceptable level. An obvious and common choice is to discharge the capacitors via a power resistor. That is where my thinking started when I set out to build a simple discharger for myself.

I envisaged a power resistor mounted in a small case with a couple of banana jacks so I could use standard test leads to discharge the capacitors in question.

I wanted a discharger good for voltages up to about 400V DC, making it suitable for off-line switch-mode power supplies and vintage valve gear. I wanted it to be able to handle this voltage indefinitely, so the discharger would not be destroyed if it was accidentally left connected or was connected when power was applied.

For example, a 10W resistor would need a value of 16kΩ or more to be permanently connected across a 400V supply – any lower, and the 10W rating would be exceeded.

However, a 10W resistor running at its rated power can get hot enough to burn skin (or even boil water!). So you might instead use a value of about 33kΩ to keep temperatures reasonable, giving a maximum dissipation of 4.85W ($400V^2 \div 33k\Omega$).

The problem with a resistive discharge circuit is that the capacitor voltage will fall exponentially, as shown in Fig.1. The figure shows the normalised capacitor voltage on the vertical axis and time on the horizontal axis.

The decay time depends on the circuit time constant τ, given by the

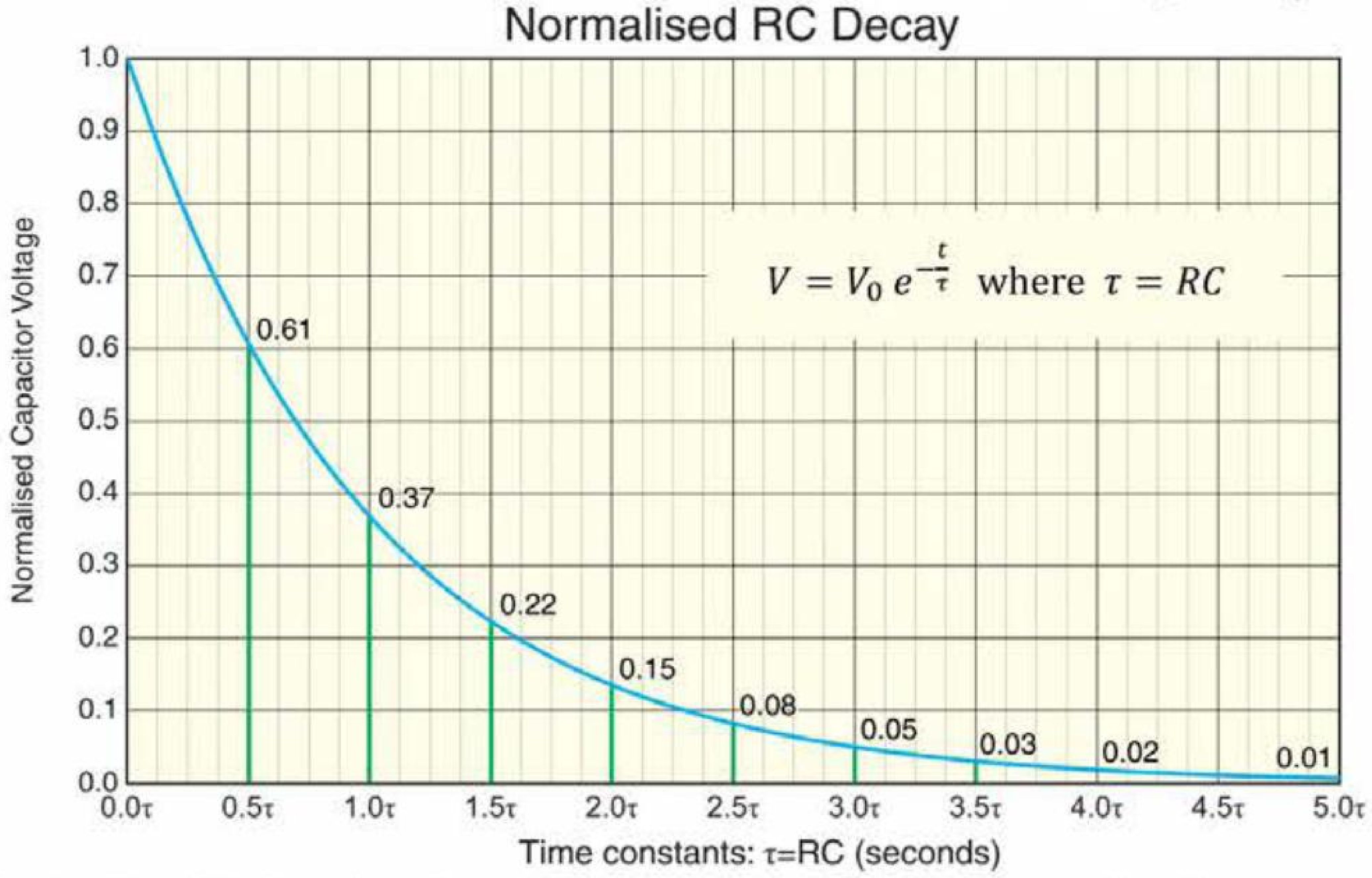


Fig.1: when discharging via a resistor, the voltage across a capacitor decays exponentially at a rate determined by the time constant τ, which is the product of the resistance and capacitance.

product of resistance and capacitance. The numbers adjacent to the curve indicate the level of discharge achieved after a given number of time constants.

The graph shows that discharging a capacitor from 400V down to a safe level (less than say 10V) will take about four RC time constants. With a 1000µF capacitance and 16kΩ or 33kΩ resistance, the discharge would take 64 or 132 seconds (about one/two minutes) – way too long in my book.

We can calculate the average power dissipated in the resistor during this process by dividing the energy stored in the capacitor by the time taken to discharge it. The energy stored in a capacitor is $\frac{1}{2}CV^2$, which works out to 80J in our example.

We know the discharge time is 64/132 seconds, giving us an average power dissipation of 1.25W/0.6W. Neither seems like an efficient use of the resistor's power rating. At the start of discharge, the resistor draws 25mA/12mA from the capacitors, with an instantaneous power dissipation of 10W/5W, but it decreases rapidly as the capacitor voltage falls.

What if we could draw a constant 25mA and discharge the capacitor this way?

We know that the relationship between the current in a capacitor and the voltage across it is $I = C \times \Delta V/\Delta t$. This means the capacitor voltage will fall linearly at a rate of $-I/C$ with a constant discharge current. In our example, this will be -25V per second, discharging to 10V in just under 16 seconds, four to eight times faster than using a resistor.

The peak power dissipation will be 10W, but the average will now be 5W – much better.

That is all good, but I still had to develop a simple circuit that would sink a relatively constant 25mA over a wide voltage range. It should also be polarity independent, since I wanted to be able to use the discharger without worrying about which lead goes where (one of the benefits of simple resistors...).

Circuit details

The resulting circuit is shown in Fig.2. The capacitor to be discharged connects via banana jacks CON3 and CON4, and a normally-closed thermal switch, to the diode bridge formed by diodes D1 to D4. The diode bridge means that it does not matter which way the capacitor is connected; either way, the positive voltage gets applied to the drain of Mosfet Q1 and the negative voltage to its source.

The discharge current flows through LED1, giving a handy visual indication that the capacitor is discharging.

The remaining part of the circuit is the current sink proper. The Mosfet is biased on via the string of three 47kΩ resistors. Three resistors are used to get sufficient voltage and power ratings, as almost all of the input voltage appears across them (a 1W resistor is generally capable of handling 400V DC, but it's better to be safe than sorry!).

As the Mosfet begins to conduct, the voltage across the 27Ω resistor rises until it reaches around 650mV, at which point transistor Q2 begins to switch on, pulling the Mosfet gate down and restricting the current through the Mosfet's channel to approximately 25mA.

The zener diode is required to ensure the Mosfet gate-source voltage never exceeds a safe level, particularly during start-up.

You may be wondering why I used a 600V, 13A TO-220 Mosfet for an application with a maximum current of 25mA. The reason for the voltage rating should be obvious, but since we are operating this Mosfet in the linear mode, it is the power dissipation rather than the current rating that is critical. This Mosfet needs to dissipate up to 10W, so I used a TO-220 package device mounted on a heatsink.

Most of the parts in the circuit are fitted to a PCB housed in a small plastic enclosure. The Mosfet and the thermal switch are both mounted on a

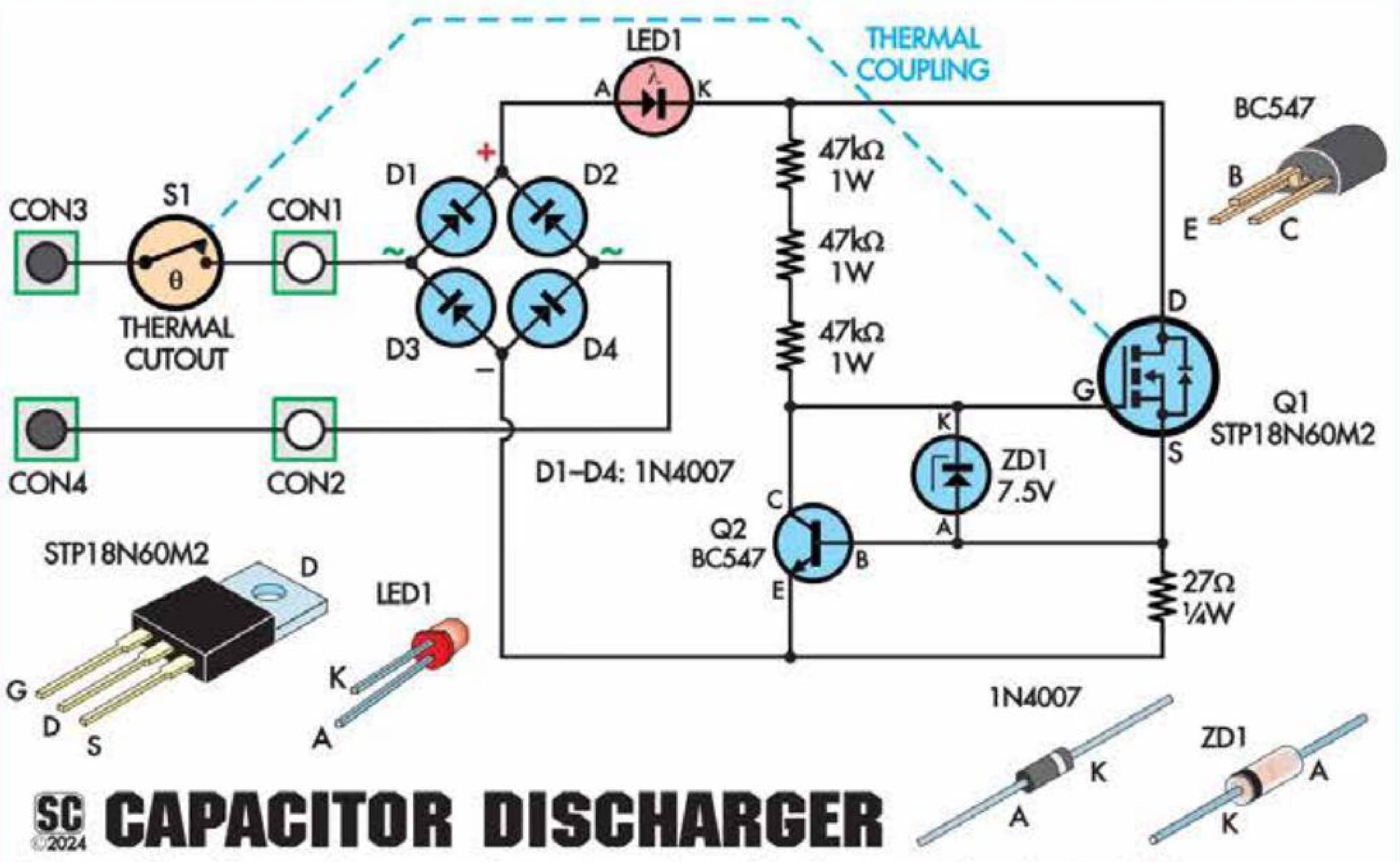


Fig.2: this shows the complete capacitor discharger circuit. It sinks a relatively constant 25mA from 10V to over 400V.

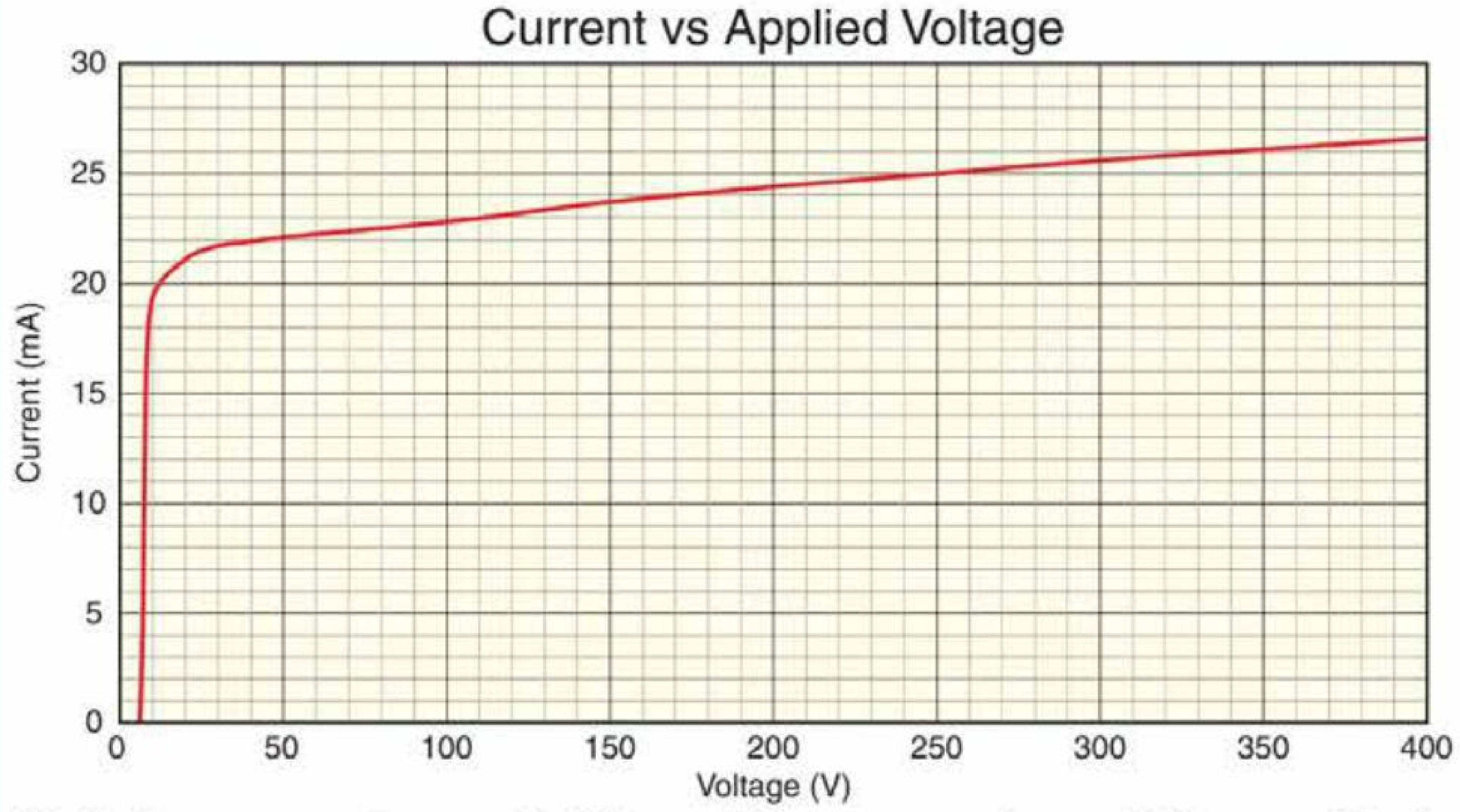


Fig.3: the measured current of the prototype ranges from a little over 26mA at 400V down to about 16mA at 8V. That's enough to discharge all but the largest capacitors reasonably quickly.

heatsink formed from a piece of aluminium angle.

The thermal switch is a fail-safe device that disconnects the circuit if the heatsink temperature reaches 90°C. That should never happen under regular use, but it prevents overheating if the discharger is left connected for extended periods while power is applied.

In practice, the discharge current is not perfectly regulated, as shown in Fig.3. The measured current for my unit was 26.6mA at 400V, dropping to around 20mA at 10V and 16mA at 8V. Below this, there is insufficient voltage to bias the Mosfet on, so the current drops almost to zero.

The LED lights when a charged capacitor is connected; it goes out when the capacitor voltage drops to less than 10V, giving a useful indication that discharging is complete and the circuit is safe. Keep in mind that the LED will also go out if the thermal breaker trips, but that's pretty unlikely in normal use, and you would hear it if it did (assuming you do not have severe hearing loss).

The LED colour is not critical but if you use one with a higher forward voltage (like green, blue or white), it will stop discharging at a slightly higher voltage.

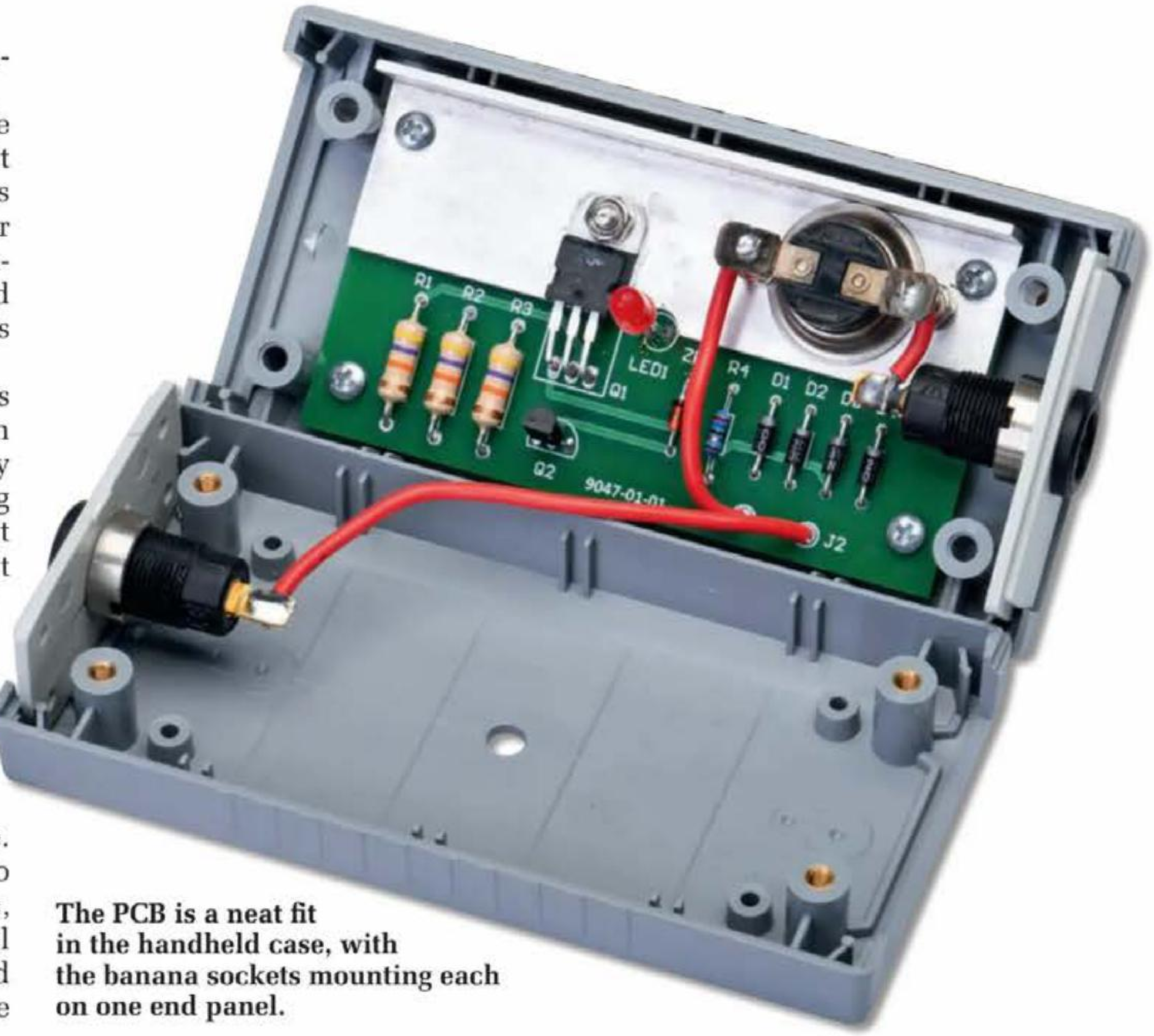
If you want to be sure (to be sure), you can always check the capacitor's final voltage with a DVM before proceeding to work on the circuit. If you see the voltage increasing, don't freak out! That is a phenomenon called dielectric charge absorption. It is very common in large electrolytic capacitors; unloaded, they can recover quite a bit of their initial charge over time.

Because of that, you may want to leave the discharger connected to the capacitor for a while, to make very sure it's drained before working on the device!

Construction

Construction is very straightforward. The Capacitor Discharger is built on a double-sided board coded 9047-01 that measures 90 × 50mm. Refer to the PCB overlay diagram, Fig.4, to see which parts go where. Fit the diodes first, ensuring they are in the correct positions and have all the cathode stripes facing the top of the board.

Then mount the resistors, followed


R1
R2
R3
LED1
Q1
Q2
R4
D1
D2
9047-01-01
J2

The PCB is a neat fit in the handheld case, with the banana sockets mounting each on one end panel.

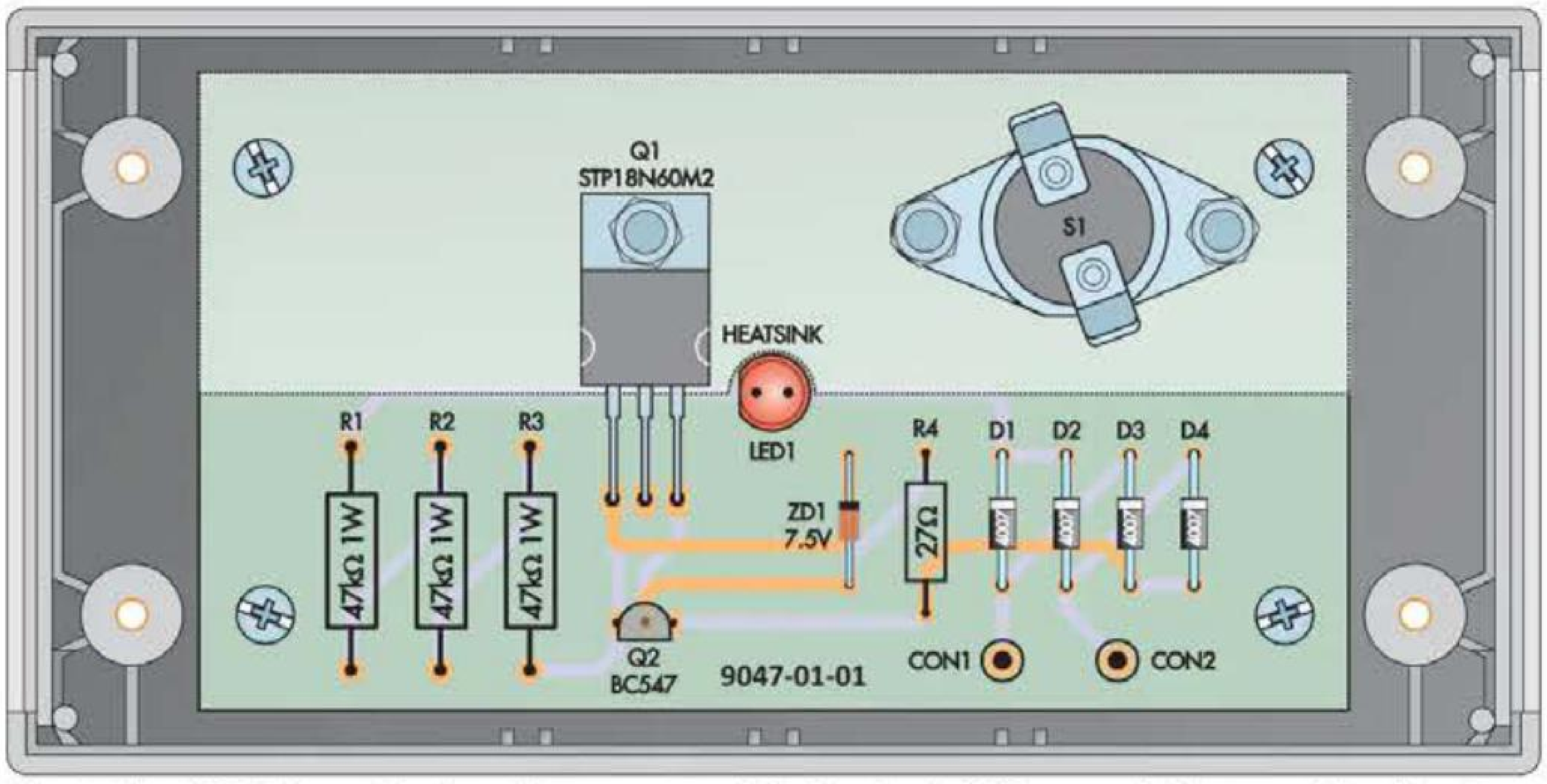

Q1
STP18N60M2
S1
HEATSINK
LED1
R1
R2
R3
R4
D1
D2
D3
D4
47kΩ 1W
47kΩ 1W
47kΩ 1W
ZD1
7.5V
27Ω
Q2
BC547
9047-01-01
CON1
CON2

Fig.4: the PCB is quite simple, so assembly is straightforward. Ensure the diodes, LED and transistors are orientated correctly and avoid dry joints; it should work first time.

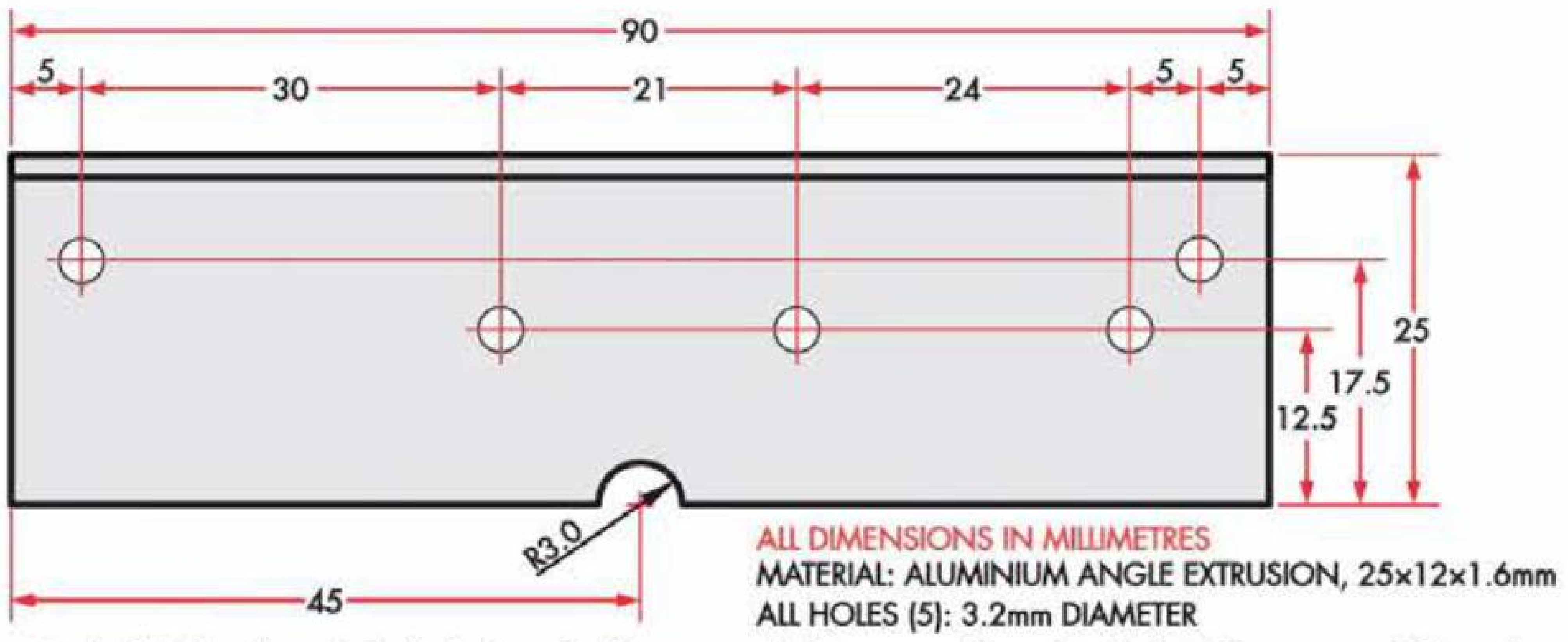

90
5
30
21
24
5
5
25
17.5
12.5
R3.0
45
ALL DIMENSIONS IN MILLIMETRES
MATERIAL: ALUMINIUM ANGLE EXTRUSION, 25×12×1.6mm
ALL HOLES (5): 3.2mm DIAMETER

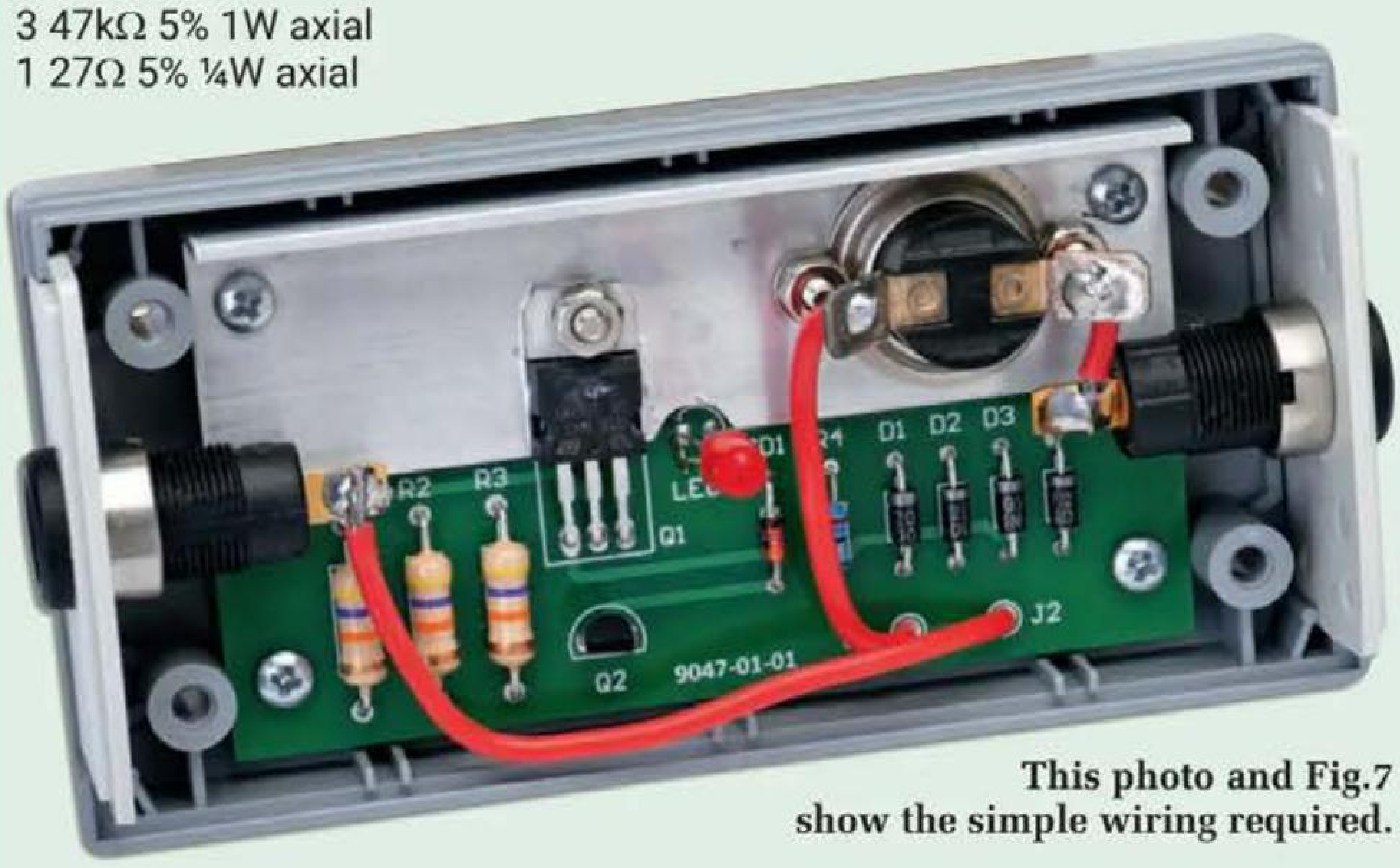
Fig.5: drill the heatsink (aluminium angle) according to this diagram. The shape of the semi-circular cutout is not critical as long as there is room for the LED leads to clear the heatsink.

Parts List – Capacitor Discharger

1 double-sided PCB coded 9047-01, 90 × 50mm
1 Gainta G436 dark grey 120 × 60 × 30mm ABS plastic moulded enclosure
  [TME G436, FIRMA PIEKARZ 11883]
1 90°C normally-closed (NC) thermal switch (S1)
  [Farnell 1006844, 4205780 or 4205759]
2 panel-mounting banana jack sockets (CON3, CON4)
  [Farnell 3518750, 3581087 or similar]
1 pair of mains-rated probes with banana plugs
1 90mm length of 25 × 12 × 1.6mm aluminium angle
3 M3 × 10mm panhead machine screws, flat & shakeproof washers & nuts
4 No.4 × 6mm self-tapping screws
1 small tube of thermal paste
1 150mm length of mains-rated hookup wire

Semiconductors
1 STP18N60M2 or AOT10N60 600V 10A Mosfet or equivalent, TO-220 (Q1)
  [Silicon Chip SC4571, Farnell 2807284, DigiKey 497-13971-5-ND]
1 BC547 45V 100mA NPN transistor, TO-92 (Q2)
1 red 5mm 30mA LED (LED1) **[Farnell 2322131]**
1 7.5V 0.4W or 1W zener diode, DO-41 (ZD1)
4 1N4007 1kV 1A diodes, DO-41 (D1-D4)

Resistors
3 47kΩ 5% 1W axial
1 27Ω 5% ¼W axial



This photo and Fig.7 show the simple wiring required.

Silicon Chip Capacitor Discharger Kit (SC7404, ~£15 + P&P): *includes the PCB, resistors, semis, mounting hardware (no heatsink) and banana sockets.*

by the small transistor, with its flat face orientated as shown. Leave the Mosfet and LED off the board for now.

The heatsink bracket is made by cutting 90mm from a piece of standard 25 × 12 × 1.6mm aluminium 'unequal angle', drilled as shown in Fig.5. The semi-circular cutout at the bottom centre of the heatsink is to clear the LED leads. Its exact shape is not critical; it can be formed by hand with a round file.

Once drilled and deburred, the bracket can be attached to the PCB by mounting the thermal switch with two M3 × 10mm machine screws with washers and nuts. The screws should be installed from the bottom of the board to ensure they don't interfere with the case. Use a dab of heatsink compound under the thermal switch.

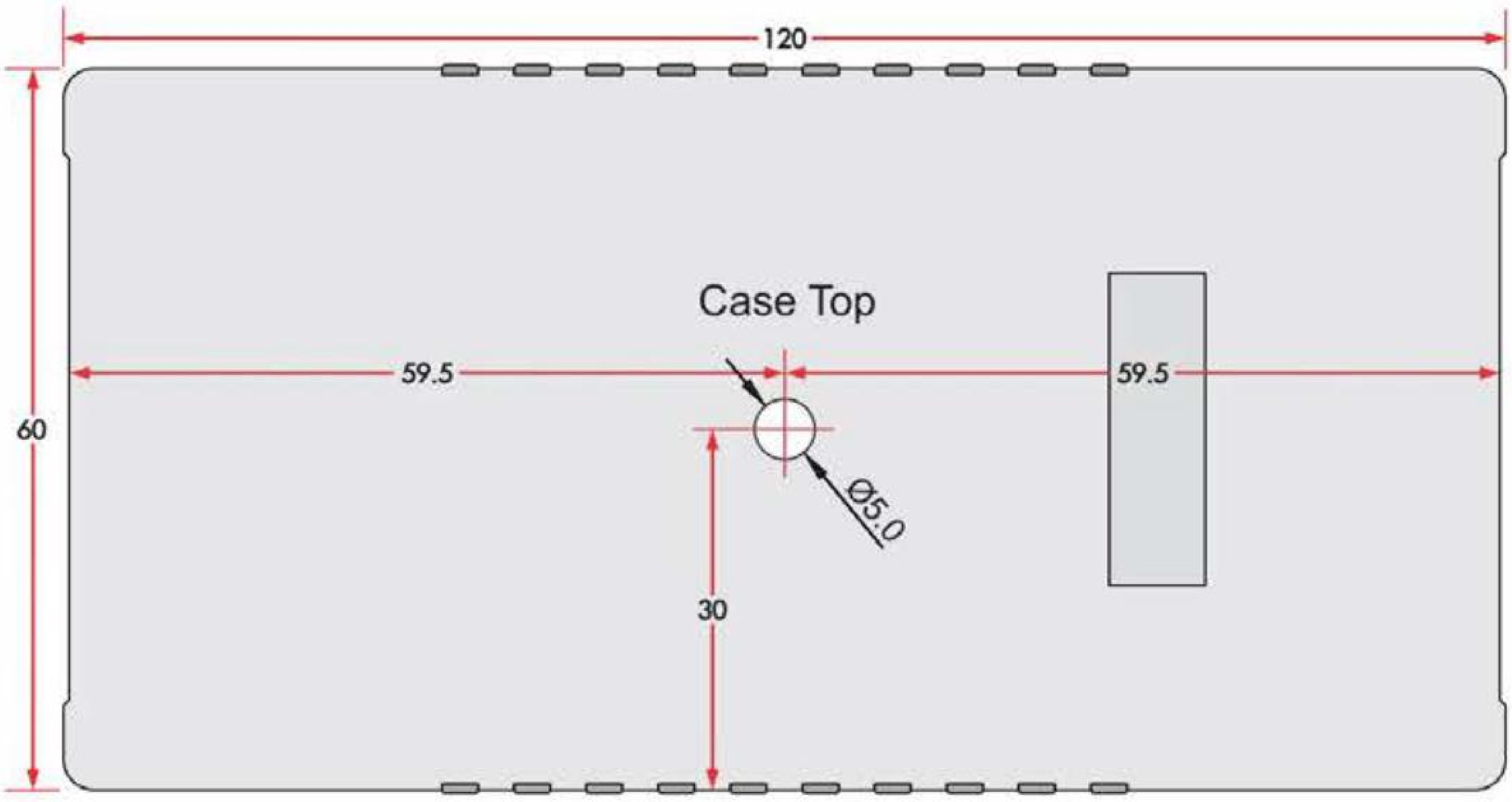
Make sure to line up all the holes in this step. You may need to carefully bend the terminals of the switch down to about 45° to allow the lid to be fitted.

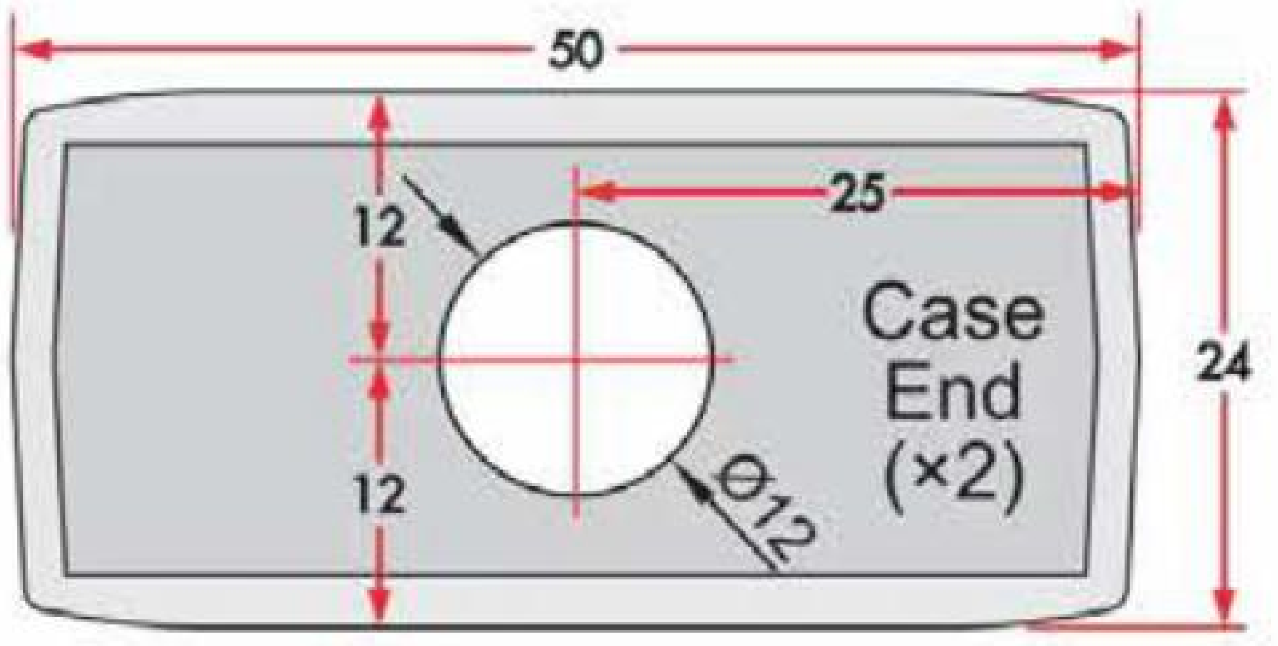
Bend the Mosfet leads and fit this using another M3 × 10mm screw, with a nut and washers in the same way. Again, use heatsink compound under the Mosfet. Carefully tighten the Mosfet down before soldering so you don't put any undue strain on the leads.

Now drill a 5mm hole right in the centre of the case top for the LED, plus two 12mm holes, centred in both end plates for the banana jacks, as shown in Fig.6. Test-fit the PCB into the case and clip the LED's leads to the correct length so its lens just protrudes through the hole in the top of the case when assembled. Then you can solder it in permanently.

Finally, fit a couple of wires to the CON1 and CON2 pads on the PCB.

Fig.6: one 5mm hole is required in the top of the case for the LED, plus one 12mm hole in each end plate for the banana jacks.





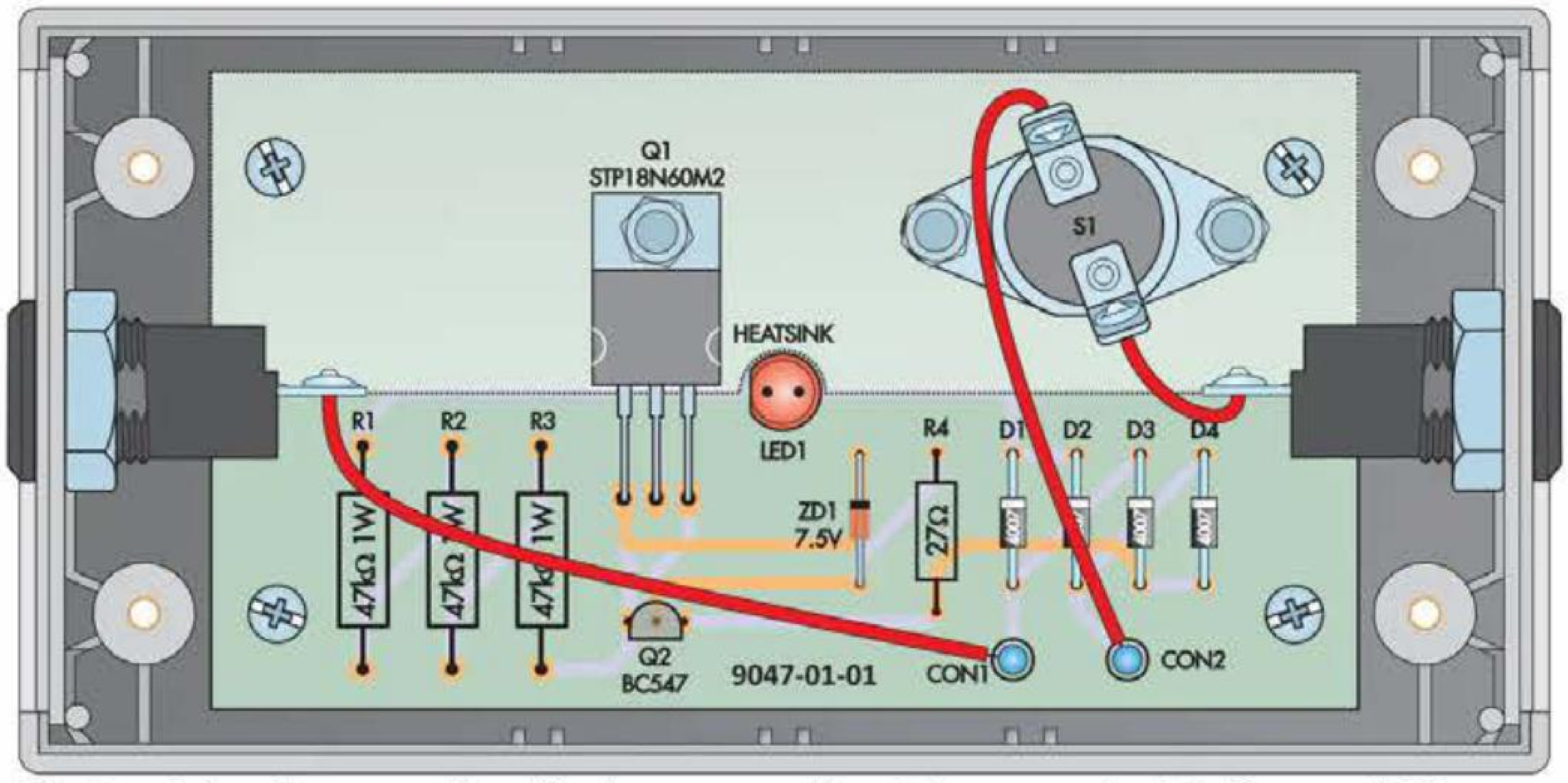


Fig.7: wiring the capacitor discharger could not be more straightforward. Use any handy mains-rated hookup wire, as the maximum current is 25mA.

After that you can wire up the connectors and thermal switch as shown in Fig.7. The wire doesn't need to be thick but it should have mains-rated insulation to ensure it will withstand up to 400V.

Finally, you can screw the board down using 6mm self-tapping screws and close up the box.

Testing & operation

To check that the Capacitor Discharger is working, you can connect it (either way) across a power supply and adjust the voltage. You should see the LED light and a current draw in the region of 18-25mA at any voltage above about 10V.

Using it is as simple as connecting a pair of test probes to each side of any potentially charged capacitors – I use a cheap pair I picked up online. Remember that high voltages might be applied to those test probes; don't use really cheap ones if you will be applying 400V DC!

Still, in our experience, you don't need to spend much money to get clips with decent insulation.

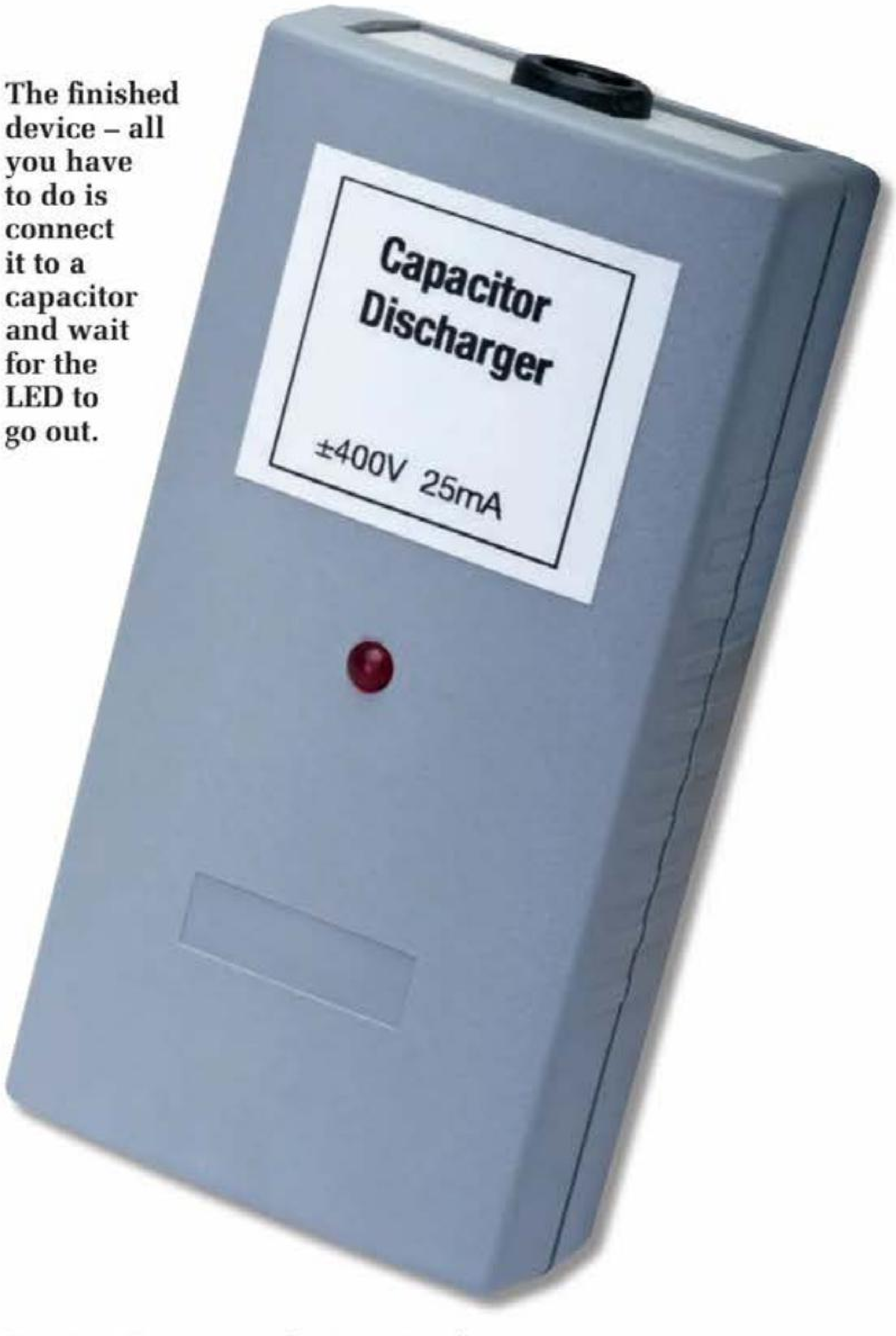
If the LED lights when the clips are attached, the capacitor is charged, so hold the probes in place until it goes out.

It should only take a matter of seconds if it's a single capacitor, although a large capacitor bank like in a power amplifier could take longer to fully discharge.

In the case of an amplifier with two capacitor banks (positive and negative), you can connect it across both banks to discharge them at the same time.

This simple, low-cost project is well worth building if you are intending to develop or service any high-voltage devices. PE

The finished device – all you have to do is connect it to a capacitor and wait for the LED to go out.



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Teach-In 2026

by Mike Tooley

World of Wireless – An Introduction to Radio and Wireless Technology

Series 12, part 1: Welcome to the World of Wireless!

Step into the fascinating world of radio and wireless technology with our latest Teach-In series. It is designed to illuminate the science, innovation and electronic technology behind the devices and systems that connect our world.

Over ten engaging parts, you will embark on a journey that traces the origins and evolution of wireless communication, explores the fundamental principles of radio frequency (RF) circuits and delves into the modern marvels of software-defined radio, Wi-Fi, Bluetooth and more.

We will begin by setting the historical stage, highlighting major milestones and scientific breakthroughs from the earliest theories to the advanced systems of today. You'll discover what radio truly is, learn how electromagnetic waves travel across the RF spectrum and understand key concepts such as frequency, wavelength and wave propagation in different bands.

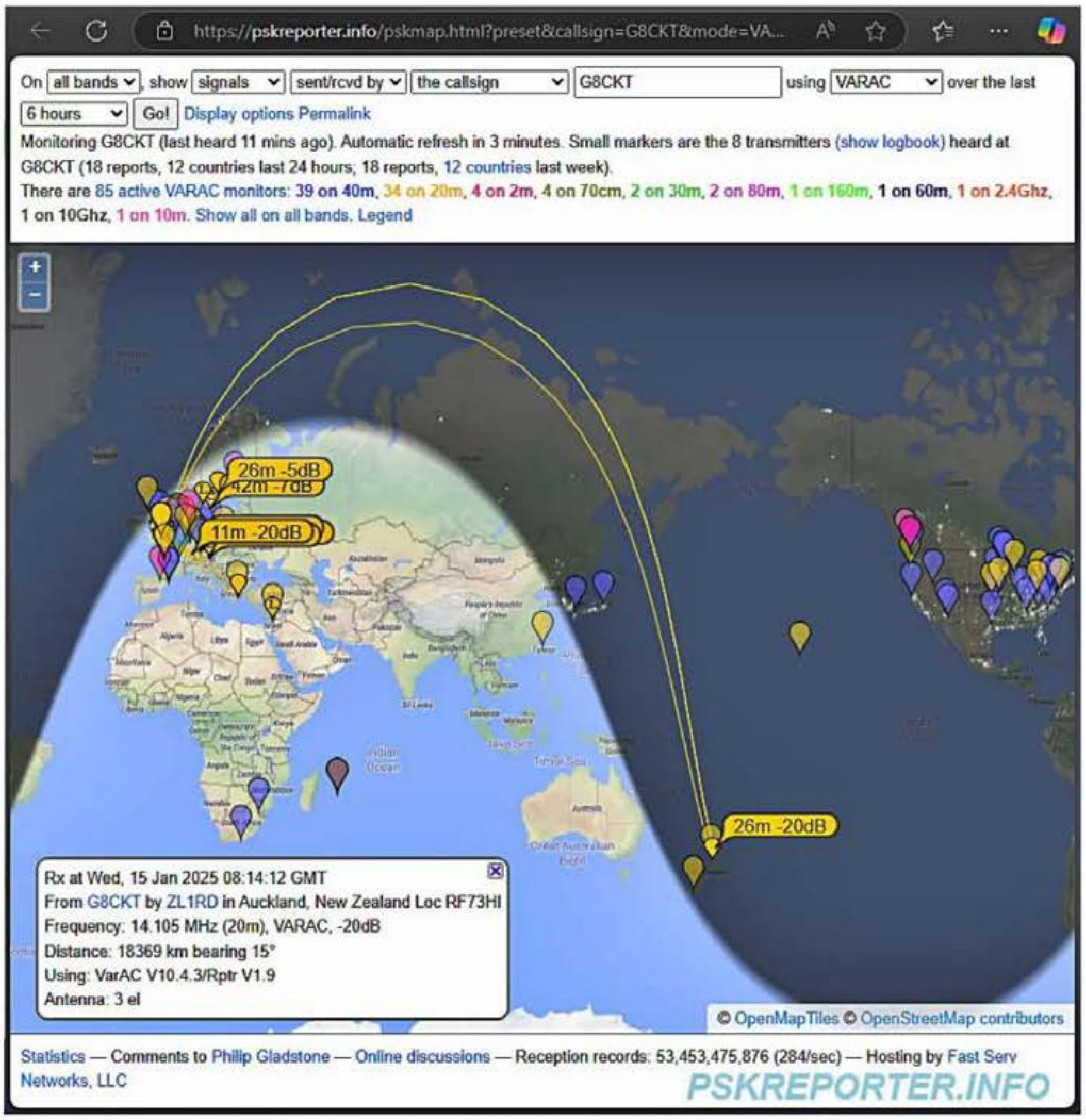
The series will then guide you through the essentials of RF circuits, the construction and operation of tuned circuits, oscillators and amplifiers. It will introduce you to the magic of crystal sets and phase-locked loops. With practical advice on building and using antennas, measuring RF signals and constructing your own simple devices, you'll be well equipped to experiment and innovate.

As we proceed, we'll unravel the complexities of radio communication systems, exploring methods of modulation and demodulation. We'll look at the art of transmitting information over long distances and the principles behind both analogue and digital transmissions, including cutting-edge digital technologies like PSK and FT8 (see Fig.1.1).

The series also opens the door to the dynamic world of modern wireless communications. Discover how Wi-Fi and Bluetooth work, how to extend wireless networks at home and how microcomputers like Arduino and Raspberry Pi are revolutionising connectivity.

You'll get experience with RF measurement tools, virtual network analysers and spectrum analysis using a software-defined radio (SDR), learning how to test and optimise performance (see Fig.1.2).

For those drawn to the excitement of two-way communication, there will be dedicated sections on amateur radio, hand-held radio devices and aircraft radio systems. You'll learn not just the technical essentials but also



https://pskreporter.info/pskmap.html?preset&callsign=G8CKT&mode=VA...

On all bands, show signals sent/rcvd by the callsign G8CKT using VARAC over the last 6 hours

Monitoring G8CKT (last heard 11 mins ago). Automatic refresh in 3 minutes. Small markers are the 8 transmitters (show logbook) heard at G8CKT (18 reports, 12 countries last 24 hours; 18 reports, 12 countries last week).

There are 85 active VARAC monitors: 39 on 40m, 34 on 20m, 4 on 2m, 4 on 70cm, 2 on 30m, 2 on 80m, 1 on 160m, 1 on 60m, 1 on 2.4Ghz, 1 on 10Ghz, 1 on 10m. Show all on all bands. Legend

Rx at Wed, 15 Jan 2025 08:14:12 GMT
From G8CKT by ZL1RD in Auckland, New Zealand Loc RF73HI
Frequency: 14.105 MHz (20m), VARAC, -20dB
Distance: 18369 km bearing 15°
Using: VarAC V10.4.3/Rptr V1.9
Antenna: 3 el

© OpenMapTiles © OpenStreetMap contributors

Statistics — Comments to Philip Gladstone — Online discussions — Reception records: 53,453,475,876 (284/sec) — Hosting by Fast Serv Networks, LLC

PSKREPORTER.INFO

Fig.1.1: low-power intercontinental communication is made possible using modern data modes such as FT8 and PSK. This shows a link being established between amateur radio stations in the UK and New Zealand using PSK Reporter software.

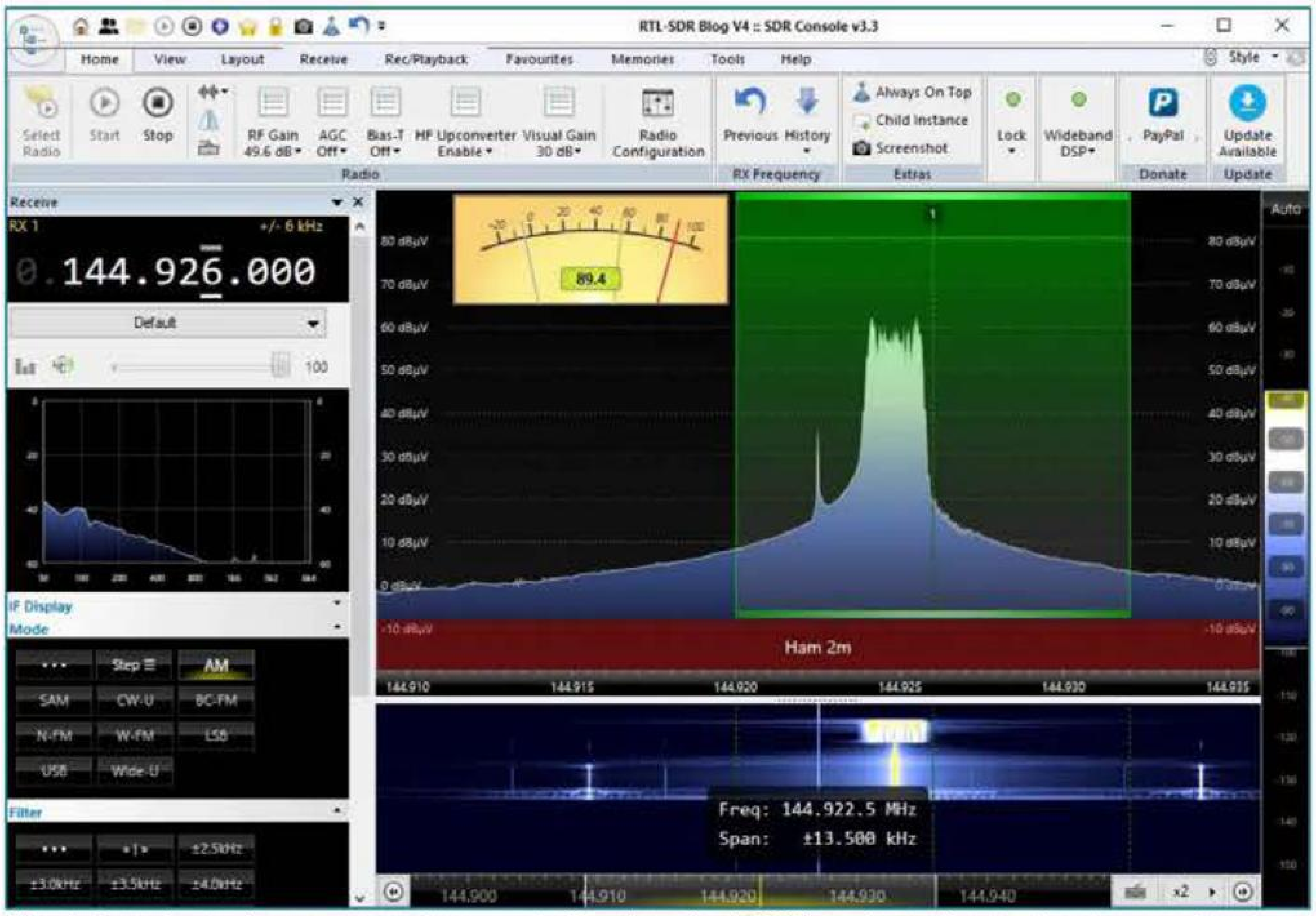

RTL-SDR Blog V4 :: SDR Console v3.3
Home
View
Layout
Receive
Rec/Playback
Favourites
Memories
Tools
Help
Select Radio
Start
Stop
RF Gain 49.6 dB
AGC Off
Bias-T Off
HF Upconverter Enable
Visual Gain 30 dB
Radio Configuration
Previous
History
Always On Top
Child Instance
Screenshot
Lock
Wideband DSP
PayPal
Update Available
RX 1
+/- 6 kHz
0.144.926.000
Default
IF Display
Mode
Step
AM
SAM
CW-U
BC-FM
N-FM
W-FM
LSB
USB
Wide-U
Filter
±2.5kHz
±3.0kHz
±3.5kHz
±4.0kHz
89.4
Ham 2m
Freq: 144.922.5 MHz
Span: ±13.500 kHz
144.910
144.915
144.920
144.925
144.930
144.935
Auto

Fig.1.2: using a low-cost software-defined radio (SDR) to investigate the transmitted signal spectrum produced by a low-cost 144MHz 'walkie talkie'.

how to join the global community of radio enthusiasts, obtain a licence and participate in activities like radio 'fox hunting' and direction finding.

Whether you're a newcomer eager to grasp the basics, or a seasoned practitioner looking to deepen your understanding, this series provides a roadmap through the rich landscape of wireless technology. Prepare to tune in, reach out and discover the invisible forces that make modern communication a reality.

Setting the scene

Radio-frequency signals typically span a range from several tens of kilohertz (kHz, 10^3Hz) to several hundred gigahertz (GHz, 10^9Hz).

The lower segment of this spectrum, particularly frequencies below 30kHz, is limited to narrow-band communication due to practical constraints. At such low frequencies, signal propagation primarily occurs as ground waves that follow the Earth's curvature, enabling transmission over extensive distances.

Conversely, the upper portion of the radio frequency range, extending beyond 30GHz into the microwave region, offers substantial bandwidth. It suits applications like point-to-point television transmission and advanced high-definition radar systems. At these higher frequencies, signal propagation generally requires line-of-sight (LOS) paths.

Signals at certain frequencies, such as those within the range from 3-30MHz, can travel long distances via ionospheric reflection, enabling intercontinental communication.

The radio spectrum is divided into bands for convenience, with each band's use determined mainly by its propagation characteristics.

Some considerations include the efficiency of aerial systems within the relevant range and the available bandwidth. Competition for frequencies is intense, and little space remains unallocated.

Frequency allocations are made through international agreements, with each user group fiercely protecting its assigned spectrum. Table 1.1 summarises radio spectrum allocations from 30kHz to 30GHz, covering bands from LF to SHF.

Radio waves

Like light, radio waves originate from a transmitter and are made up of electric (E) and magnetic (H) fields at right angles to each other. These interconnected fields form an electromagnetic wave that travels outward, with both E and H vectors orthogonal to the direction of propagation, as shown in Fig.1.3.

Radio waves are said to be polarised in the plane of the electric (E) field. Thus, if the E-field is vertical, the signal is said to be vertically polarised whereas if the E-field is horizontal, the signal is said to be horizontally polarised.

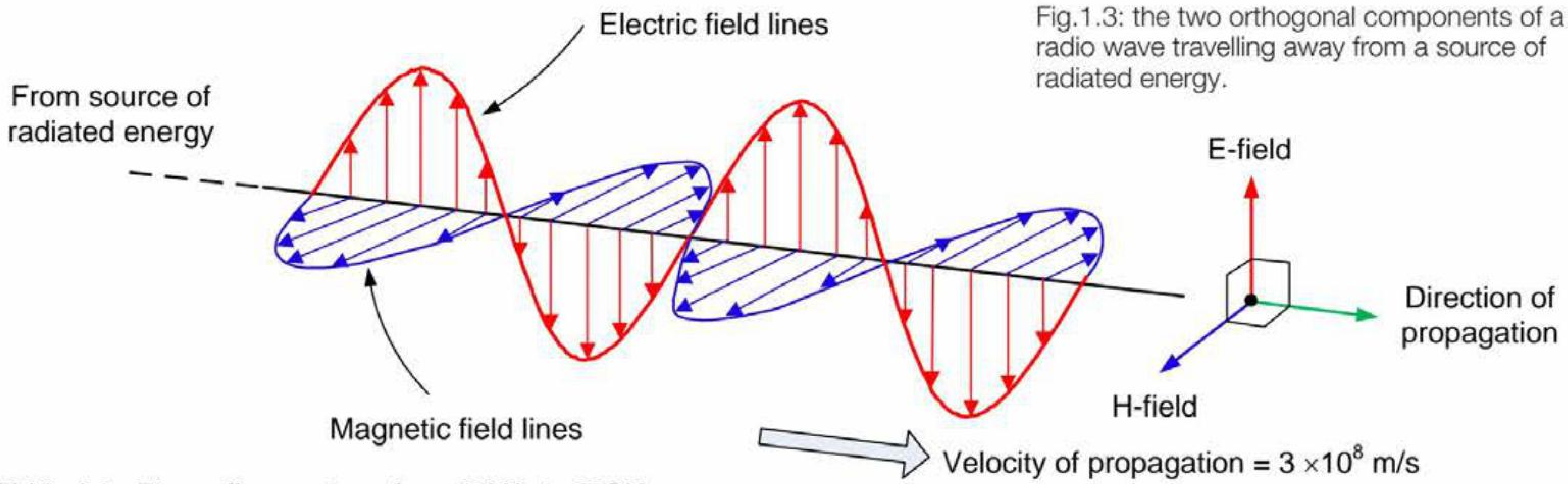

Electric field lines
From source of radiated energy
E-field
Direction of propagation
H-field
Magnetic field lines
Velocity of propagation = 3 ×10⁸ m/s

Fig.1.3: the two orthogonal components of a radio wave travelling away from a source of radiated energy.

Table 1.1 – The radio spectrum from 30kHz to 30GHz

Designation	Range	Common applications
Low frequency (LF)	30-300kHz	Submarine communication, time signals
Medium frequency (MF)	300kHz to 3MHz	Navigational beacons, AM broadcasting (530-1700kHz), amateur radio
High frequency (HF)	3-30MHz	Shortwave broadcasting (various bands), amateur radio, aviation, military uses
Very high frequency (VHF)	30-300MHz	FM broadcasting (88-108MHz), aviation, marine, DAB, military uses
Ultra-high frequency (UHF)	300MHz to 3GHz	TV broadcasting, mobile phones, Wi-Fi, Bluetooth, satellite navigation (eg, GPS)
Super-high frequency (SHF)	3-30GHz	Radar, satellite TV, point-to-point microwave links, Wi-Fi

A Brief History of Radio

James Clerk Maxwell (1831-1879) first suggested the existence of electromagnetic waves in 1864. Later, Heinrich Hertz (1857-1894) used an arrangement of rudimentary resonators to demonstrate the existence of electromagnetic waves.

Hertz's apparatus was extremely simple and comprised two resonant loops, one for transmitting and the other for receiving. Each loop acted both as a tuned circuit and as a resonant antenna (or 'aerial').

Hertz's transmitting loop was excited by an induction coil and battery. Some of the energy radiated by the transmitting loop was intercepted by the receiving loop, and the received energy was conveyed to a spark gap where it could be released as an arc.

The energy radiated by the transmitting loop was in the form of an electromagnetic wave—a wave that has both electric and magnetic field components, and travels at the speed of light.

In 1894, Guglielmo Marconi (1874-1937) demonstrated the commercial potential of the phenomenon that Maxwell predicted and Hertz used in his apparatus. It was also Marconi who made radio a reality by pioneering the development of telegraphy without wires ('wireless').

Marconi was able to demonstrate very effectively that information could be exchanged between distant locations without the need for a landline.

Marconi's system of wireless telegraphy proved to be invaluable for maritime communications (ship-to-ship and ship-to-shore) and was instrumental in saving many lives, including when the Titanic sank in 1912.

The military applications of radio were first exploited during the First World War (1914 to 1918). Radio broadcasting took shape early in the 1920s, with many listeners using crystal sets and simple one- or two-valve receivers. Broadcasting quickly took on a national dimension, with radio becoming the principal source of entertainment in most households.

Significant technological advancements were made in the two decades leading up to the Second World War (1939-1945). Among the most notable were the introduction of single sideband (SSB) transmission for long-distance voice communication, frequency modulation (FM) for high-fidelity broadcasting and television transmission in the VHF band (30-300MHz).

Following the Second World War, car and portable radios became common and more affordable with the advent of transistors in the 1950s. At the same time, stereophonic broadcasting began in the UK. Communication and navigation satellites were introduced and microwave point-to-point links were established. Colour television followed in the 1960s.

From the 1980s onwards, radio started to embrace the digital revolution by providing a means of transmitting digital data without the need for a wire or cable connection. Satellite and terrestrial links extended the range, availability and bandwidth. The start of the 21st century saw the introduction and wide availability of low-cost wireless networks, including Wi-Fi (IEEE 802.11).

Table 1.2 (opposite) shows some important milestones in the development of radio and wireless technology.

Fig.1.4 shows the electric E-field lines in the space between a transmitter and a receiver. The transmitter antenna (a dipole) is fed with high frequency alternating current. This gives rise to an alternating electric field between the ends of the antenna and an associated alternating magnetic field around and at right angles to it.

The direction of the electric field lines alternates with each cycle of the signal as the wavefront propagates from the source. The receiving antenna detects the changing field, resulting in a similar voltage and current being induced in it, but at a lower amplitude.

In Fig.1.4, where the transmitter and receiver are close (in the near field), the field spreads out spherically. However, at greater distances (the far field), the wavefront becomes planar and the angular distribution of the field no longer depends on the distance between the antennas.

Frequency and wavelength

Radio waves propagate in air (or space) at the speed of light (approximately 300 million metres per second). The velocity of propagation, v, wavelength, λ and frequency, f, of a radio wave are related by the equation $v = (f \times \lambda)$m/s.

This equation can be arranged to make f or λ the subject, ie, $f = (v \div \lambda)$Hz or $\lambda = (v \div f)$m. v is the velocity of propagation ($\sim 3 \times 10^8$m/s in air or space).

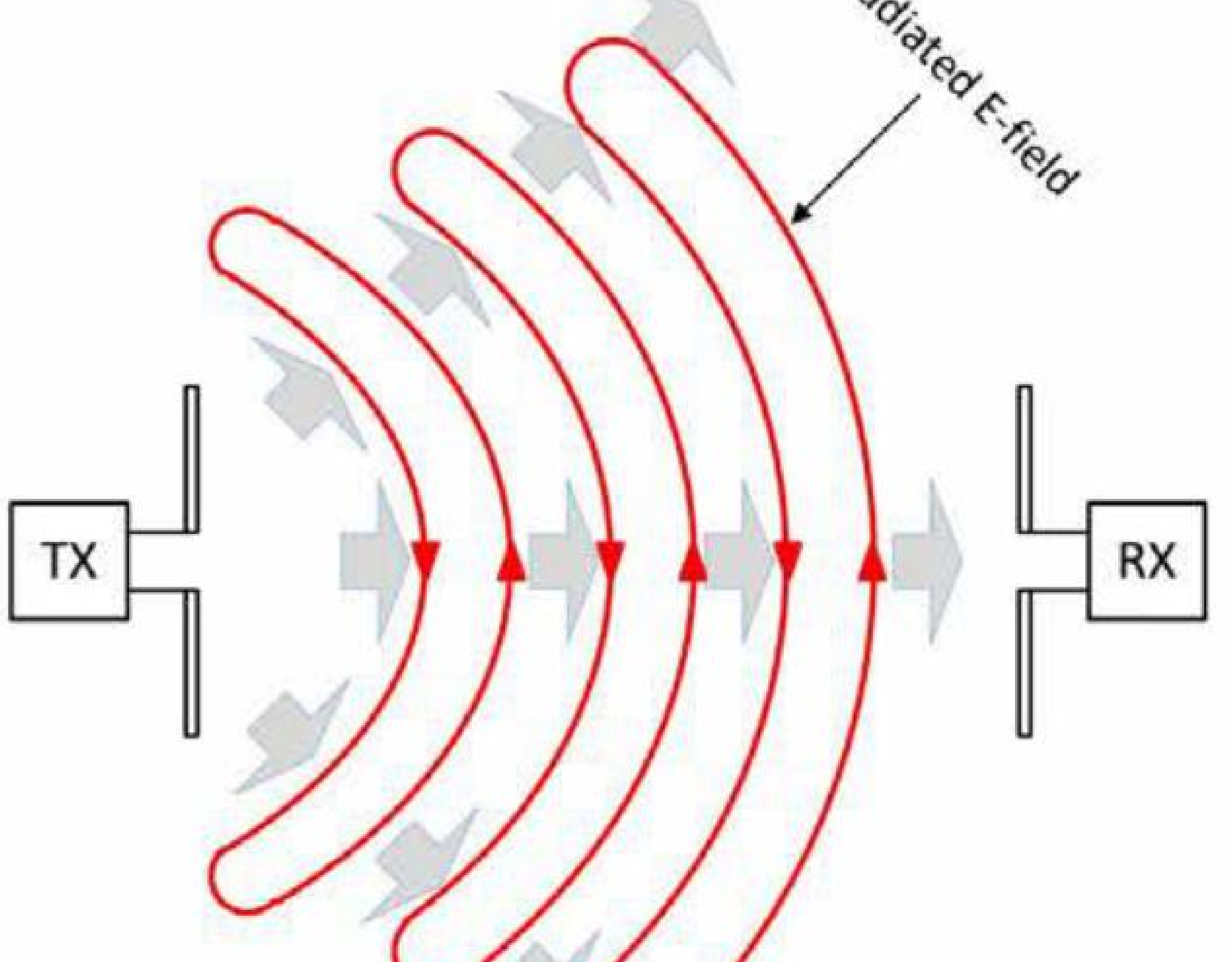


Fig.1.4: the electric field pattern in the near-field region between a transmitter and a receiver.

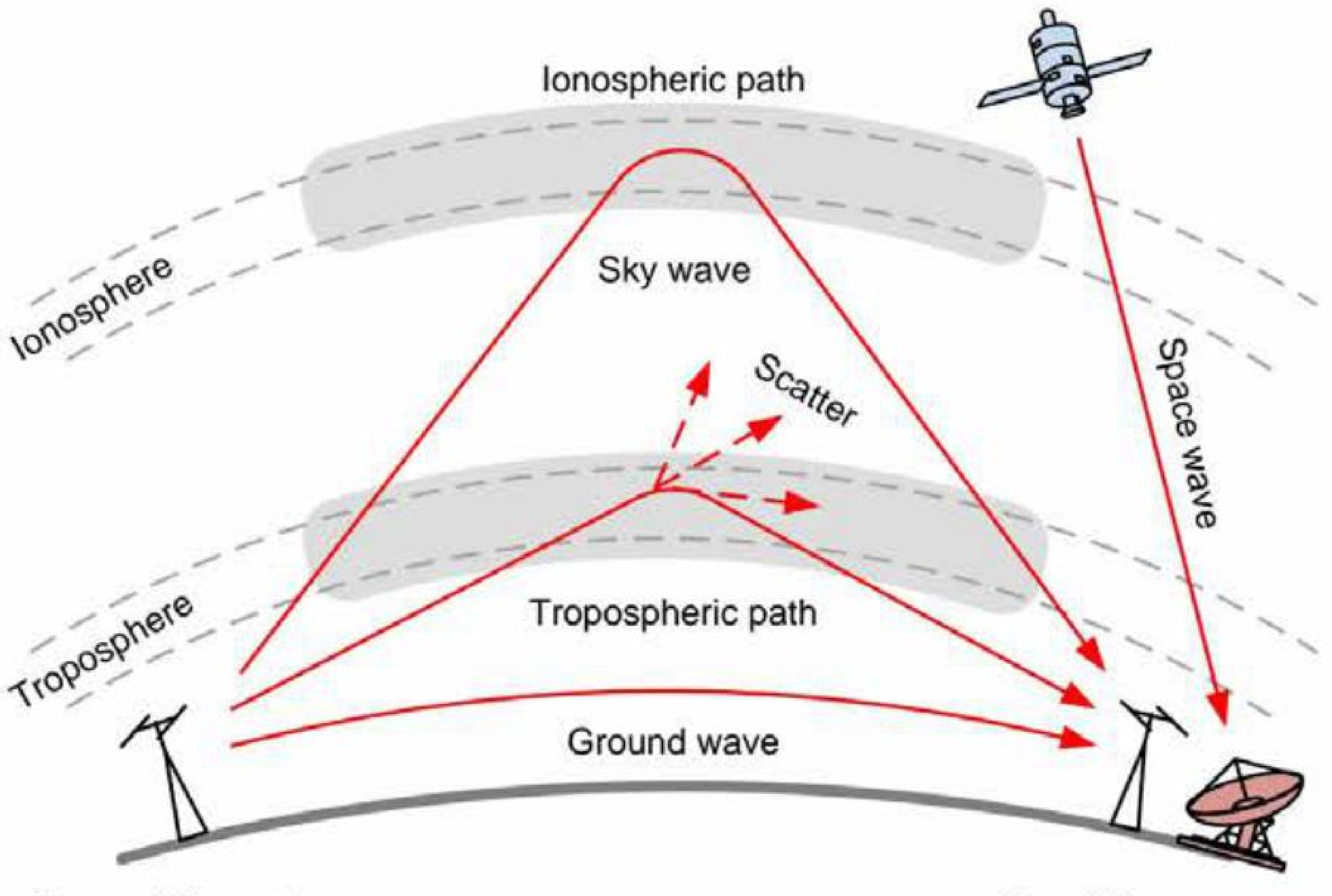


Fig.1.5: various modes of radio wave propagation through the atmosphere; note how signals can take more than one path between two points.

Table 1.2 – The history of radio and wireless technology

Year	Event
1864	Maxwell predicts the existence of radio waves and lays the theoretical foundation for radio and wireless communication
1888	Hertz generates and successfully detects electromagnetic waves in a Berlin laboratory
1895	Marconi demonstrates wireless telegraphy over a few miles and gains commercial interest in its exploitation
1901	Marconi sends the letter "S" in Morse code from Cornwall, England to Newfoundland, Canada
1906	Fessenden transmits voice and music from Brant Rock, Massachusetts, USA
1920	The world's first commercial broadcast station (KDKA) opens in Pittsburgh, Pennsylvania, USA
1921	Radio amateurs demonstrate the possibility of transatlantic communication via radio
1922	The BBC establishes the first national public radio network in the UK
1926	The first major radio network standardises nationwide programming in the USA
1933	Armstrong patents FM, which would eventually replace AM, reducing noise and improving audio quality
1939	W47NV in Nashville, TN, USA, begins FM broadcast programming for the public
1945	After WW2, radio amateurs experiment with SSB, which becomes the standard for efficient voice transmission
1953	Radio amateurs Ross Bateman (W4AO) & Bill Smith (W3GKP) record echoes of their transmissions reflected from the moon
1954	The Regency TR-1 allows truly portable listening, fuelling radio's golden era in popular culture
1960	First two-way communication via moon bounce between radio amateurs
1961	The first amateur radio satellite, built by volunteers, transmits radio telemetry from Earth orbit
1962	Telstar 1 is the first satellite to relay across the Atlantic, paving the way for global broadcasting
1969	A network is developed that allows digital devices to communicate wirelessly
1973	GPS satellites are launched in the USA as a joint military and civil project
1978	Digital data transmission is demonstrated over radio waves, laying the groundwork for wireless networking
1981	Digital audio broadcasting is tested, promising more channels and (arguably) better sound quality
1983	The first mobile phone is made available to the public
1994	The forerunner of today's touch screen and email smartphones is created
1995	The full constellation of 24 GPS satellites becomes operational
1997	The 2.4GHz 2Mbps wireless standard heralds the start of Wi-Fi (IEEE 802.11)
1999	The first laptop computer with integrated Wi-Fi goes on sale
2000	Civilians worldwide gain access to GPS satellite signals
2011	Digital radio gains mainstream adoption, diversifying the broadcast landscape
2015	DAB is fitted as standard in many cars and domestic radios
2017	FT8, a weak-signal digital model, revolutionises low-power communication under poor propagation conditions
2020	Satellite radio reaches a global audience of 33 million subscribers

As an example, a signal at a frequency of 1MHz will have a wavelength of 300m, whereas a signal at a frequency of 100MHz will have a wavelength of 3m. Note that when a radio wave travels in a cable or waveguide (rather than in air or free space), it usually travels at 60-80% of the speed of light. We will be returning to this later in the series.

Radio wave propagation

Depending on several complex factors, radio waves propagate through the atmosphere in various ways, as shown in Fig.1.5. These include:

- ground waves
- ionospheric waves
- space waves
- tropospheric waves

As the name suggests, ground waves (or surface waves) travel close to the surface of the Earth and propagate for relatively short distances at HF and VHF, but for much greater distances at MF and LF.

For example, at 100kHz, the range of a ground wave might be more than 500km, whilst at 1MHz (using the same radiated power), the range might be no more than 150km, and at 10MHz, no more than about 15km.

Ground waves have two basic components: a direct wave and a ground reflected wave (as shown in Fig.1.6). The direct path exists on a line-of-sight (LOS) basis between the transmitter and receiver.

Examples of the use of direct paths are terrestrial microwave repeater stations, which are typically in towers spaced 20-30km apart so they have a line of sight.

The direct path is also used for satellite TV reception. To receive signals from the satellite, the receiving antenna must be able to 'see' the satellite. In this case, since the wave travels directly through the atmosphere, the direct wave is often referred to as a space wave. Such waves travel over LOS paths at VHF, UHF and beyond.

Fig.1.6 shows that signals can arrive at a receiving antenna via both the direct path and by reflection from the ground. Ground reflection depends very much on the quality of the ground, with sandy soils being a poor reflector of radio signals, and flat, marshy ground being an excellent reflecting surface.

Note that a proportion of the incident radio signal is absorbed into the ground; not all of it is usefully reflected. An example of the use of a mixture of direct path and ground (or building) reflected radio signals is the reception of FM broadcast signals in a car.

It is also worth mentioning that, in many cases, the reflected signals can be stronger than the direct path (or the direct path may not exist at all if a car happens to be in a heavily built-up area).

Ionospheric waves (or sky waves) can travel for long distances at MF, HF and exceptionally also at VHF under certain conditions. Such waves are predominant at frequencies below VHF, and we shall examine this phenomenon in greater detail a little later.

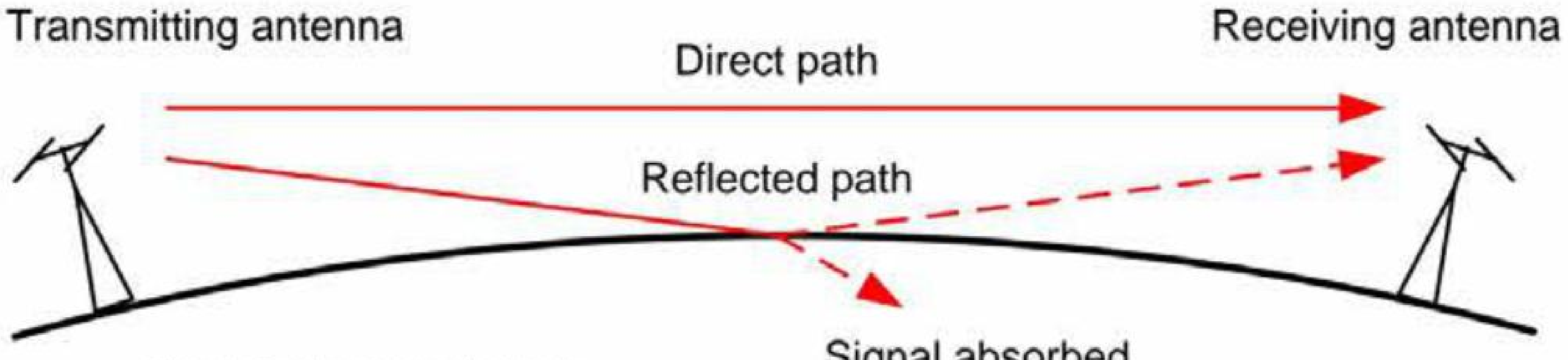


Fig.1.6: the constituents of a ground wave.

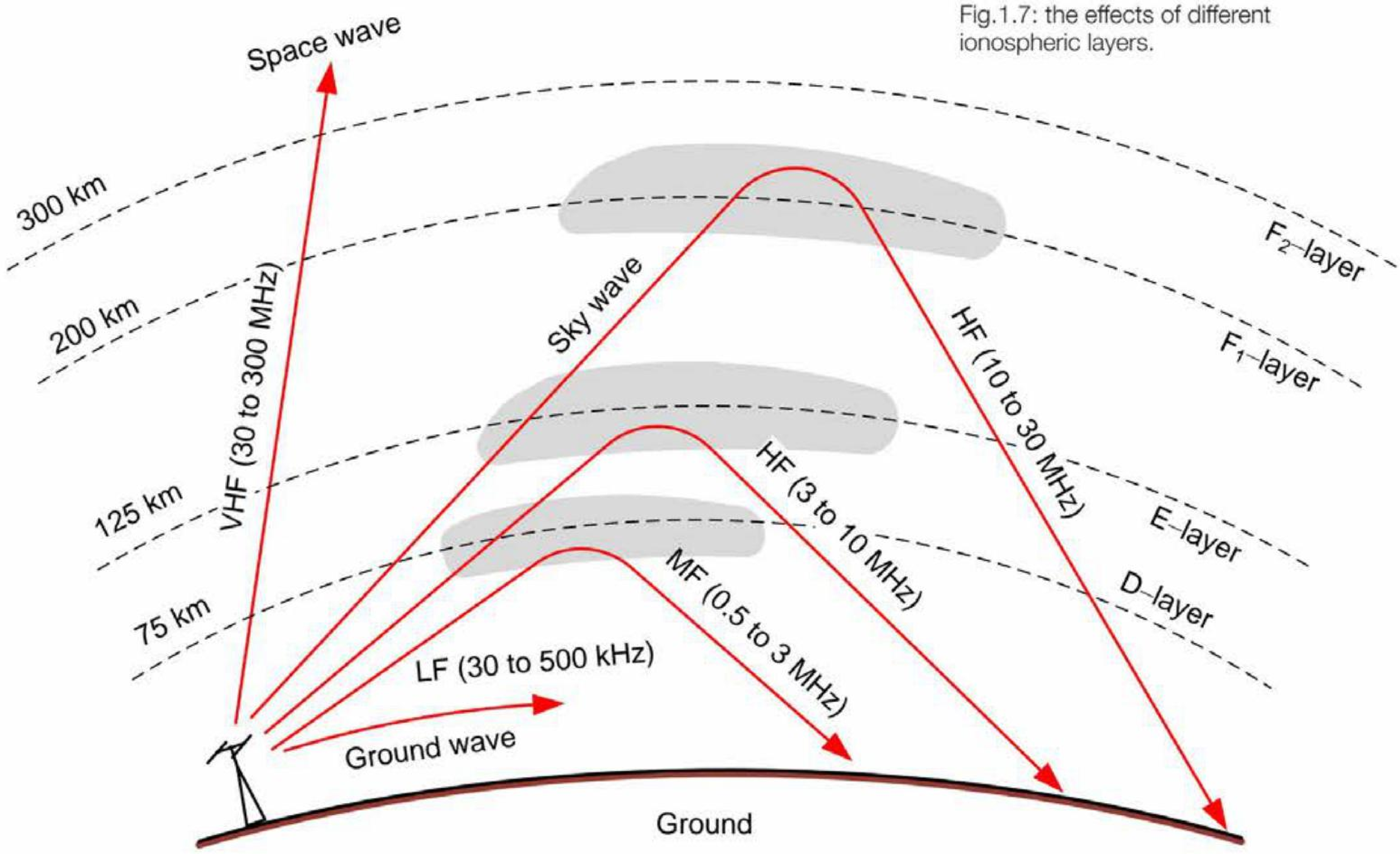


Fig.1.7: the effects of different ionospheric layers.

Still, before we do, it is worth describing what can happen when waves meet certain types of discontinuity in the atmosphere or when they encounter a physical obstruction. In both cases, the direction of travel can be significantly affected according to the nature and size of the obstruction or discontinuity. Four different effects can occur:

- reflection
- refraction
- diffraction
- scattering

Reflection occurs when a plane wave meets a plane object that is large relative to the wavelength of the signal. In such cases, the wave is returned with minimal distortion and without any change in velocity. The effect is like the reflection of a beam of light off a mirror.

Refraction occurs when a wave moves from one medium into another in which it travels at a different speed. For example, when moving from a denser to a less dense medium, the wave is bent away from the normal (an imaginary line at right angles to the boundary). Conversely, when moving from a less dense to a denser medium, a wave will bend towards the normal.

The effect is like that experienced by a beam of light when it encounters a glass prism or lens.

Diffraction occurs when a wave meets an edge (a sudden impenetrable surface discontinuity) that has dimensions that are large relative to the wavelength of the signal. In such cases, the wave is bent so that it follows the profile of the discontinuity. Diffraction occurs more readily at lower frequencies (typically VHF and below).

An example of diffraction is the bending experienced by VHF broadcast signals when they encounter a sharply defined mountain ridge. Such signals can be received at some distance beyond the 'knife edge', even though they are well beyond the normal LOS range.

Scattering occurs when a wave encounters one or more objects in its path with a size that is a fraction of the wavelength of the signal. When a wave encounters an obstruction of this type, it will become fragmented and re-radiated over a wide angle. Scattering occurs more readily at higher frequencies (typically VHF and above) and regularly occurs in the troposphere at UHF and EHF.

The troposphere extends from the Earth's surface up to 18km in the tropics, reducing to 6km in the polar regions.

Radio signals can also be directed upwards (by suitable choice of antenna) so that signals enter the troposphere or ionosphere (48-965km altitude, ionised by solar radiation). In the former case, signals can become scattered (partially dispersed) in the troposphere so that a small proportion arrives back at the ground.

Tropospheric scattering requires high-power transmitting equipment and high-gain antennas, but is regularly used for transmission beyond the horizon, particularly where conditions in the troposphere (rapid changes of temperature and humidity with height) can support this mode of communication.

Tropospheric scattering of radio waves is analogous to the scattering of a light beam shone into a heavy fog or mist.

There is also tropospheric ducting, in which radio signals can become trapped because of the change of refractive index at a boundary between air masses with different temperature and humidity. Ducting usually occurs when a large mass of cold air is overrun by warm air (a 'temperature inversion').

Although this condition may occur frequently in certain parts of the world, this mode of propagation is not very predictable and is therefore not used for any practical applications.

The ionosphere

In 1924, Sir Edward Appleton (1892-1965) was one of the first to demonstrate the existence of a reflecting layer at a height of about 100km (now called the E-layer). This was soon followed by the discovery of another layer at around 250km (now called the F-layer).

Table 1.3 – Ionised layers of the atmosphere and their effects

Layer	Altitude	Characteristics	Effect on radio waves
D	50-95km	Develops shortly after sunrise and disappears shortly after sunset. Reaches maximum ionisation when the sun is at its highest point in the sky.	Responsible for the absorption of radio waves at lower frequencies (below about 4MHz) during daylight hours.
E	95-150km	Develops shortly after sunrise and disappears a few hours after sunset. The maximum ionisation of this layer occurs at around midday.	Reflects waves below 5MHz but tends to absorb radio signals above this frequency.
E_S	80-120km	An intense region of ionisation that sometimes appears in the summer months (peaking in June/July in the Northern Hemisphere). Usually lasts for only a few hours (often in the late morning and recurring in the early evening of the same day).	Highly reflective at frequencies above 30MHz, up to 300MHz on some occasions. Of no practical use other than as a means of long-distance VHF communication for radio amateurs.
F	250-450km	Appears a few hours after sunset, when the F1- and F2-layers merge to form a single layer.	Reflects radio waves up to 20MHz and occasionally up to 25MHz.
F1	150-200km	Occurs during daylight hours with maximum ionisation reached at around midday. The F1-layer merges with the F2-layer shortly after sunset.	Reflects radio waves in the low HF spectrum, up to about 10MHz.
F2	250-450km	Develops just before sunrise as the F-layer begins to divide. Maximum ionisation of the F2-layer is usually reached one hour after sunrise, and it typically remains at this level until shortly after sunset. The intensity of ionisation varies greatly according to the time of day and season, and is greatly affected by solar activity.	Capable of reflecting radio waves in the upper HF spectrum with frequencies of up to 30MHz and beyond during periods of intense solar activity (eg, at the peak of each 11-year sunspot cycle).

This was achieved by broadcasting a continuous signal from one site and receiving the signal at a second site several miles away. By measuring the time difference between the signal received along the ground and the signal reflected from the atmosphere (and knowing the velocity at which the radio wave propagates), it was possible to calculate the height of the atmospheric reflecting layer.

Today, the standard technique for detecting the presence of ionised layers (and determining their height above the surface of the earth) is to transmit a very short pulse directed upwards into space and accurately measure the amplitude and time delay before the arrival of the reflected pulses. This ionospheric sounding is carried out over a range of frequencies.

The different layers within the ionosphere (Fig.1.7) provide us with a reasonably predictable means of communicating over long distances using MF and HF radio signals. Much short and long-distance communication below 30MHz depends on the bending or refraction of the transmitted wave in the earth's ionosphere.

The useful regions of ionisation are the E-layer (maximum ionisation at about 70mi/100km) and the F-layer (lying at about 175mi/250km at night). During the daylight hours, the F-layer splits into two distinguishable parts: F1, at a height of about 140mi/225km, and F2, at about 200mi/320km. After sunset, the F1 and F2 layers recombine into a single F-layer.

During daylight, a lower layer of ionisation known as the D-layer exists in proportion to the sun's height, peaking at local noon and largely dissipating after sunset. This lower layer primarily acts to absorb energy at the low end of the high-frequency (HF) band.

The F-layer ionisation regions are primarily responsible for long-distance communication using sky waves at distances of up to several thousand km (much more than can be achieved using VHF direct wave communication). The characteristics of the various ionised layers are summarised in Table 1.3.

Ionograms

Ionograms, like the one shown in Fig.1.8, provide us with a means of visualising prevailing ionospheric conditions at a given location and time. They are plotted from data returned from an ionospheric probe, a frequency-agile transmitting station that directs its output in a series of bursts aimed vertically into the atmosphere.

Following each burst, the signal reflected from one or more of the ionospheric layers is detected by a co-sited radio receiver. The time difference between the transmitted and received bursts is used to calculate the altitude of the reflecting layer.

Ionograms are useful for assessing and predicting radio propagation, as they show ionisation regions, their

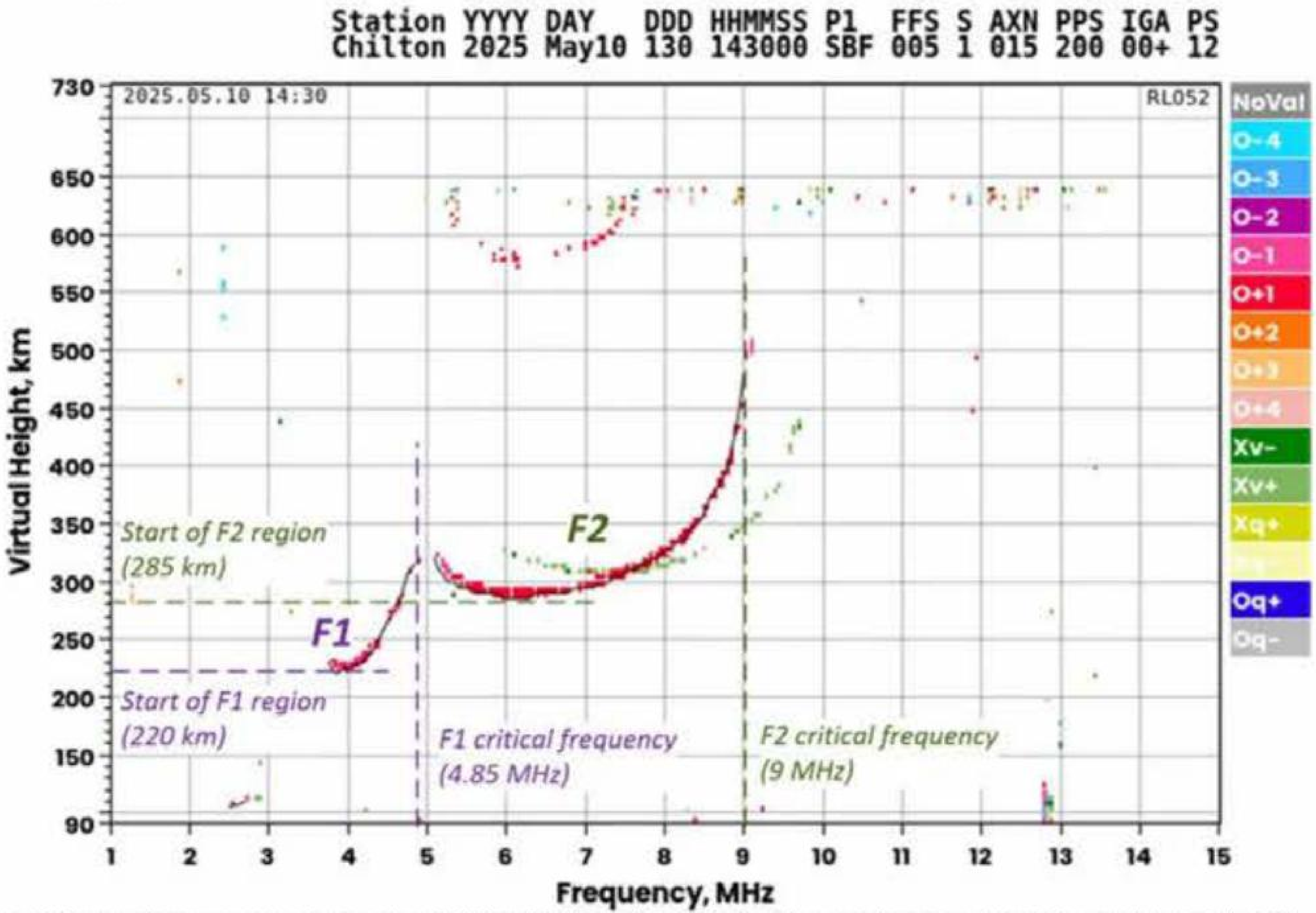


Fig.1.8: an ionogram from the UK's Chilton ionospheric station at 14:30 on the 10th of May, 2025. It clearly shows the presence of both the F1 and F2 layers.

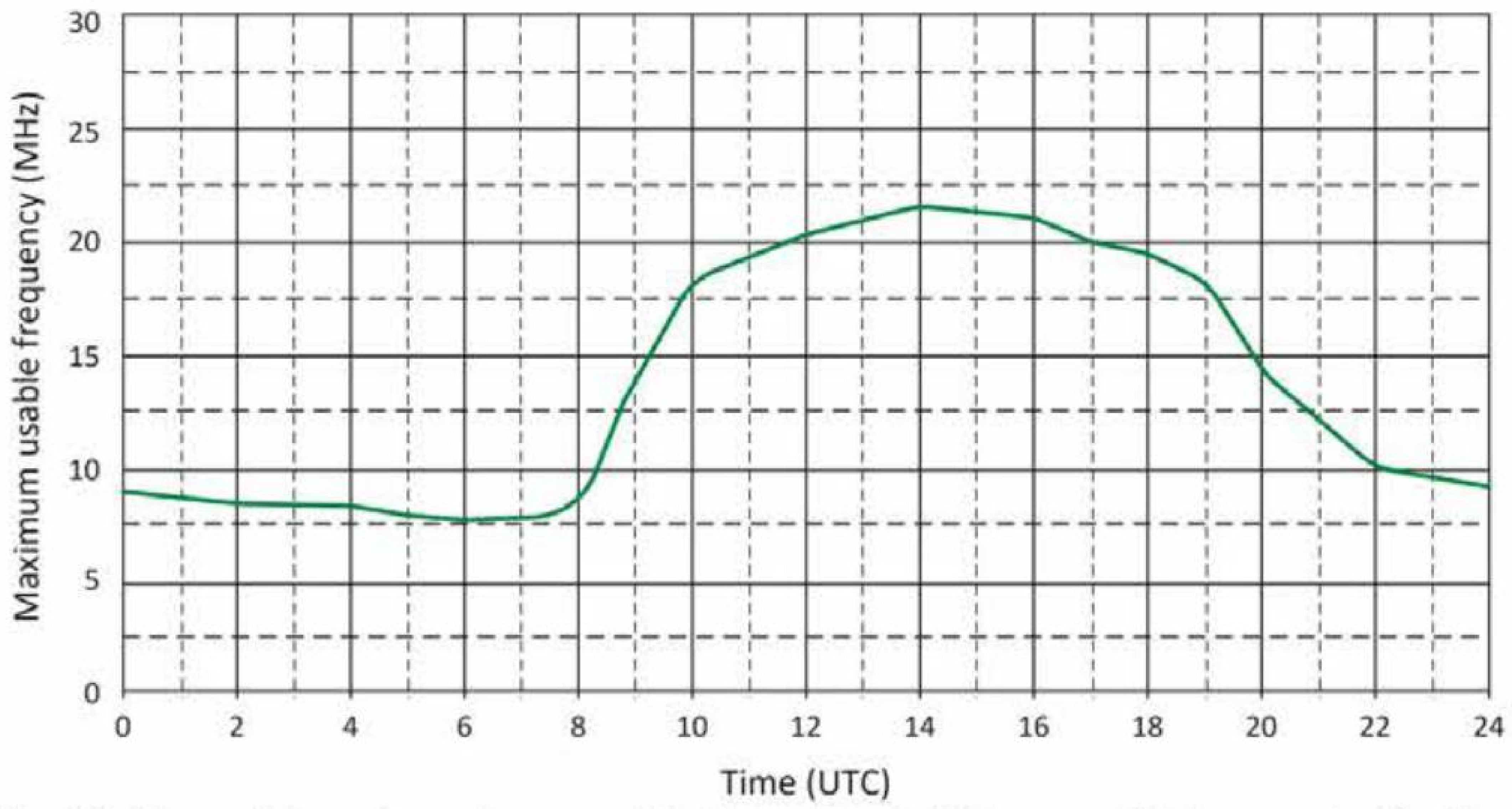


Fig.1.9: the variation of maximum usable frequency (MUF) over a 24-hour period for the radio path between London and New York.

altitude and the critical frequency—the highest vertically radiated signal reflected by a layer. Signals above this frequency pass through the ionosphere into space.

Highest & lowest usable frequencies

The maximum usable frequency (MUF) is the highest frequency that will allow communication over a given terrestrial path at a particular time and on a particular date. The MUF varies considerably with the amount of solar activity and is basically a function of the height and intensity of the F-layer.

During a period of intense solar activity, the MUF can exceed 30MHz during daylight hours, but is often around 16-20MHz by day, and around 8-10MHz by night.

The variation of the MUF over a 24-hour period for the London to New York path is shown in Fig.1.9. A similar plot for the summer months would be flatter, with a more gradual increase at dawn and a more gradual decline at dusk.

The reason for the significant variation of the MUF over any 24-hour period is that the intensity of ionisation in the upper atmosphere is significantly reduced at night. Consequently, lower frequencies have to be used to produce the same amount of refractive bending and to give the same critical angle and skip distance as by day.

Fortunately, the attenuation experienced by lower frequencies travelling in the ionosphere is much reduced at night. This makes it possible to use the lower frequencies required for effective communication. The important fact to remember from this is simply that, for a given path, the frequency used at night is about half that used for daytime communication.

The lowest usable frequency (LUF) is the lowest frequency that will support communication over a given path at a particular time and on a particular date. The LUF depends on the amount of absorption experienced by a radio wave. This absorption is worst when the D-layer is most intense (during daylight).

Hence, as with the MUF, the LUF rises during the day and falls during the night. A typical value for the LUF is 4-6MHz during the day, falling rapidly at sunset to 2MHz.

The frequency chosen for HF communication must therefore be somewhere above the LUF and below the MUF for a given path, day and time. A typical example might be a working frequency of 5MHz at a time when the MUF is 10MHz and the LUF is 2MHz.

The silent zone is the region that exists between the extent of the coverage of the ground wave signal and the point at which the sky wave first returns to earth. Note also that, depending on local topography and soil characteristics, when a signal returns to the Earth from the ionosphere, it is sometimes possible for it to experience a reflection from the ground.

The onward reflected signal will suffer attenuation but, in some circumstances, it may be sufficient to provide a further hop and an approximate doubling of the working range. This is known as multi-hop propagation. The skip distance is simply the distance between the point at which the sky wave is radiated and the point at which it returns to Earth.

Where signals are received simultaneously by ground wave and sky wave paths, the signals will combine both constructively and destructively due to the different path lengths. This, in turn, will produce an effect known as fading.

This effect can often be heard during the early evening on medium-wave (AM) radio signals as the D-layer begins to fade. You should be able to hear this effect when you complete this month's Hands-On Project.

Hands-On: A modern 'crystal set'

Each of our Teach-In instalments will feature a simple project designed to enhance learning and encourage further experimentation (see Fig.1.10). This month, we start with a modern 'crystal set' radio, which swaps the original galena crystal for an integrated circuit and two small-signal transistors—

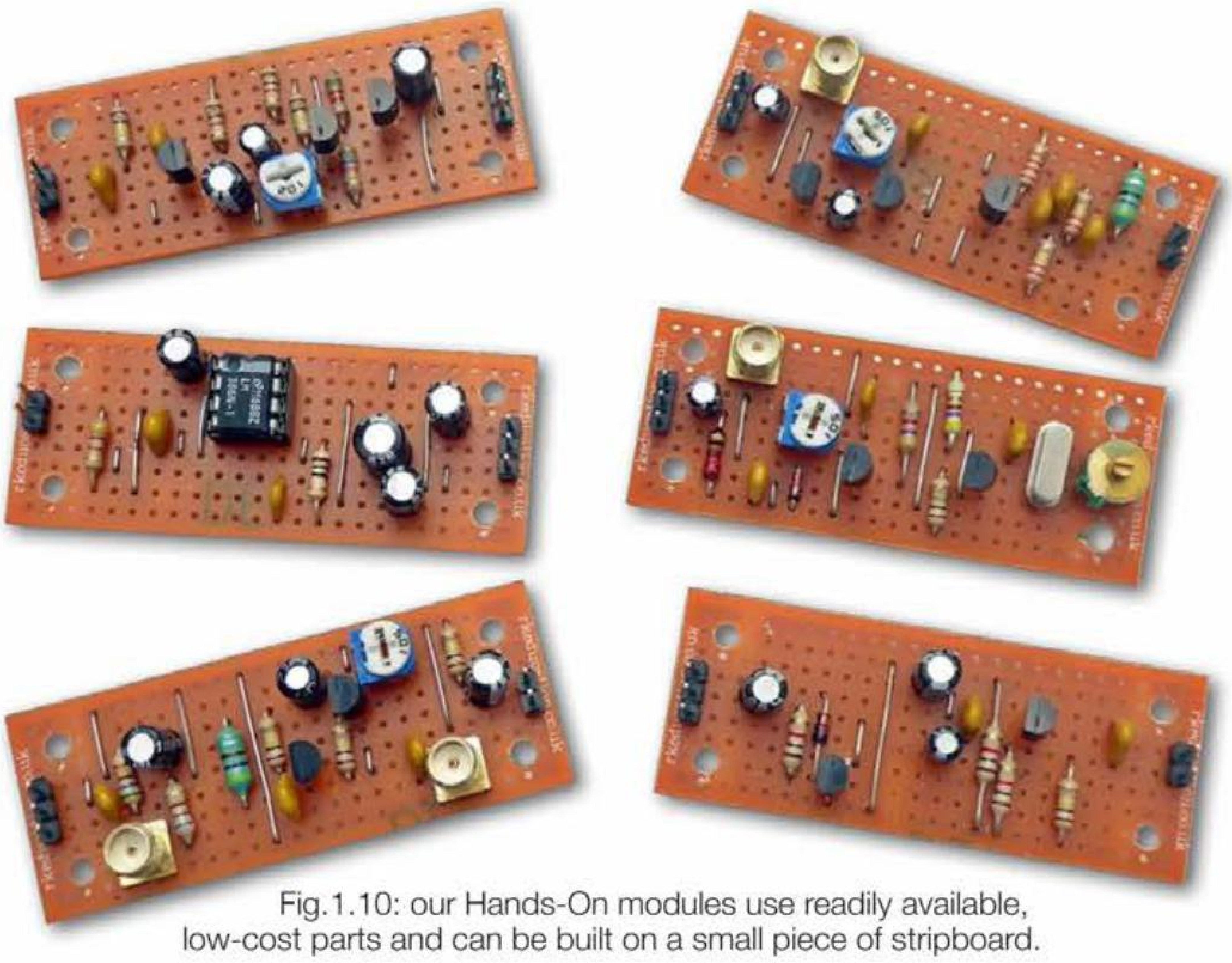
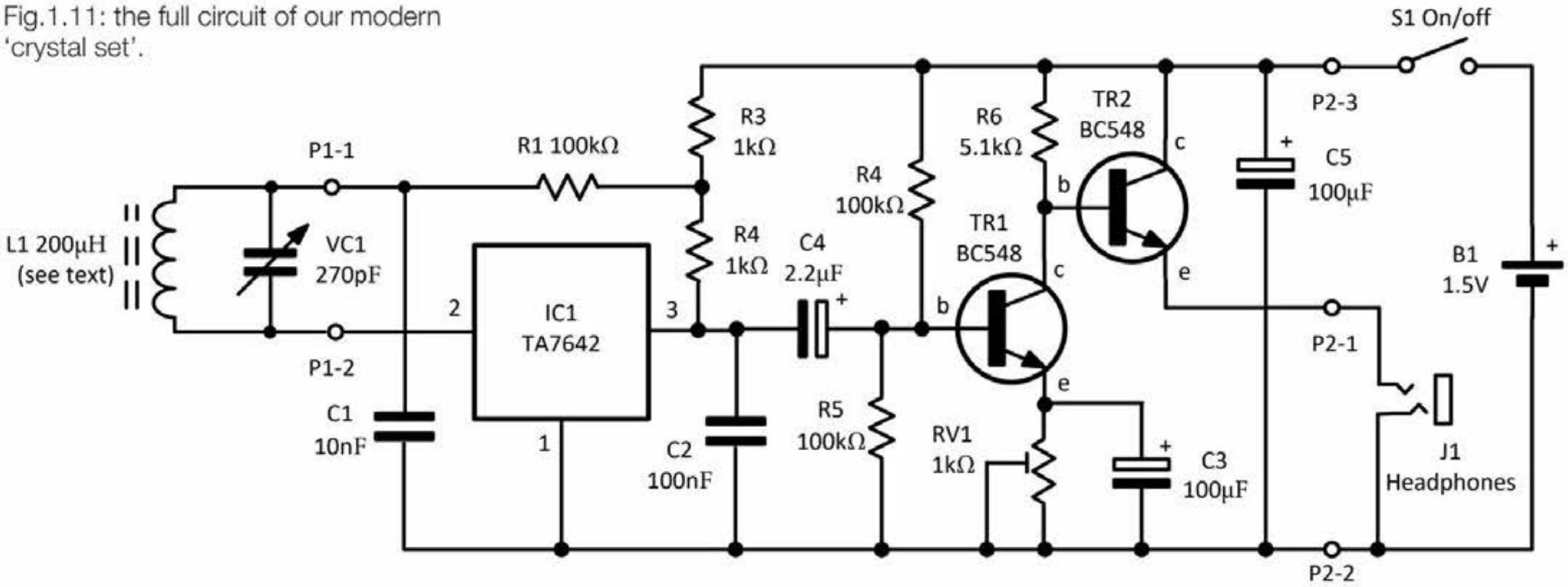


Fig.1.10: our Hands-On modules use readily available, low-cost parts and can be built on a small piece of stripboard.

Fig.1.11: the full circuit of our modern 'crystal set'.


S1 On/off
P2-3
P1-1
R1 100kΩ
R3
1kΩ
R6
5.1kΩ
TR2
BC548
c
b
e
+
C5
100µF
R4
100kΩ
L1 200µH
(see text)
VC1
270pF
R4
1kΩ
C4
2.2µF
TR1
BC548
B1
1.5V
2
IC1
TA7642
3
b
c
e
P2-1
P1-2
C1
10nF
1
C2
100nF
R5
100kΩ
RV1
1kΩ
C3
100µF
J1
Headphones
P2-2

components that were unavailable a century ago.

Our Hands-On 'crystal set' receives local medium wave (MW) transmissions using headphones and is powered from a single AA 1.5V cell. The complete circuit diagram is shown in Fig.1.11.

The receiver makes use of a hand-wound coil on a ferrite rod. Tuning is managed by L1, which also serves as the antenna, together with a small solid dielectric variable capacitor, VC1. The precise value for VC1 is not critical, but a maximum value of between 270pF and 350pF will prove ideal.

Such capacitors are often supplied with multiple sections (and some also with smaller value trimmers), in which case you can safely ignore them. The dimensions of the ferrite rod are also uncritical. The component used for the prototype receiver had a measured inductance of 200µH and was 200mm in length and 10mm in diameter.

If you cannot locate a part with these dimensions, there is plenty of scope for experimentation, but a shorter rod will usually require a few more turns of wire to obtain the same inductance value.

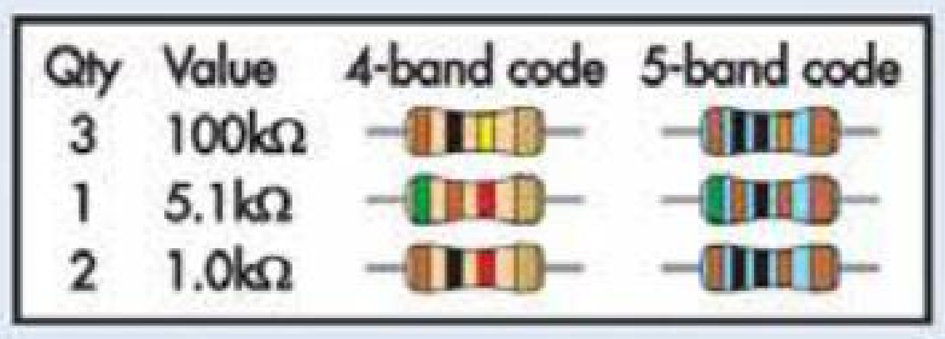
IC1 is a TA7642 single-chip radio receiver housed in a TO-92 package.

Parts List – A modern 'crystal' set

1 25 × 64mm piece of stripboard (9 × 24 holes)
1 200mm-long, 10mm diameter ferrite rod (L1)
1 1kΩ miniature horizontal trimpot (RV1)
1 ABS enclosure (optional; see text)
1 3.5mm miniature jack socket (J1)
1 SPST miniature toggle switch (S1)
1 single AA cell holder
4 brass or nylon M3 × 10mm hex stand-off spacers
4 short M3 panhead machine screws
1 2-pin male 0.1in/2.54mm header (P1)
1 3-pin male 0.1in/2.54mm header (P2)

Semiconductors
1 TA7642 single-chip radio receiver (IC1)
2 BC548 small-signal NPN transistors (TR1, TR2)

Capacitors
2 100µF 16V radial electrolytic (C3, C5)
1 2.2µF 16V radial electrolytic (C4)
1 100nF 50V ceramic (C2)
1 10nF 50V ceramic (C1)
1 270-350pF miniature solid-dielectric variable (VC1)



Qty	Value	4-band code	5-band code
3	100kΩ		
1	5.1kΩ		
2	1.0kΩ		

Resistors (all ¼W axial, 5% or better)
3 100kΩ (R1, R4, R5)
1 5.1kΩ (R6)
2 1kΩ (R2, R3)

Additional components for the optional RF gain control
1 250kΩ linear carbon track potentiometer (VR1)
1 100kΩ ¼W 5% resistor (R7)

The internal schematic of the TA7642 is shown in Fig.1.12. The chip operates from a 1.5V supply and consumes less than 1mA of current. Its silicon substrate contains ten transistors that provide

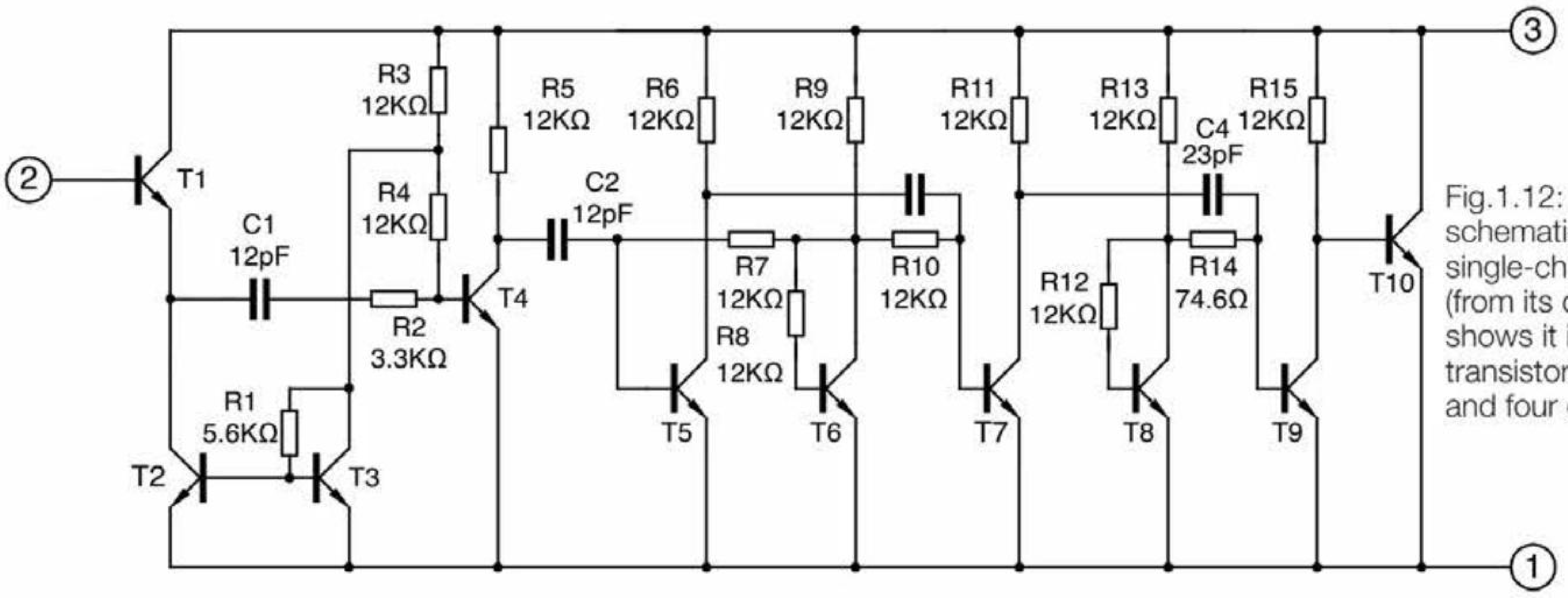

③
R3
12KΩ
R5
12KΩ
R6
12KΩ
R9
12KΩ
R11
12KΩ
R13
12KΩ
C4
23pF
R15
12KΩ
②
T1
C1
12pF
R4
12KΩ
C2
12pF
R7
12KΩ
R10
12KΩ
R12
12KΩ
R14
74.6Ω
T10
T4
R2
3.3KΩ
R8
12KΩ
R1
5.6KΩ
T5
T6
T7
T8
T9
T2
T3
①

Fig.1.12: the internal schematic of the TA7642 single-chip radio receiver (from its data sheet) shows it includes 10 transistors, 15 resistors and four capacitors.

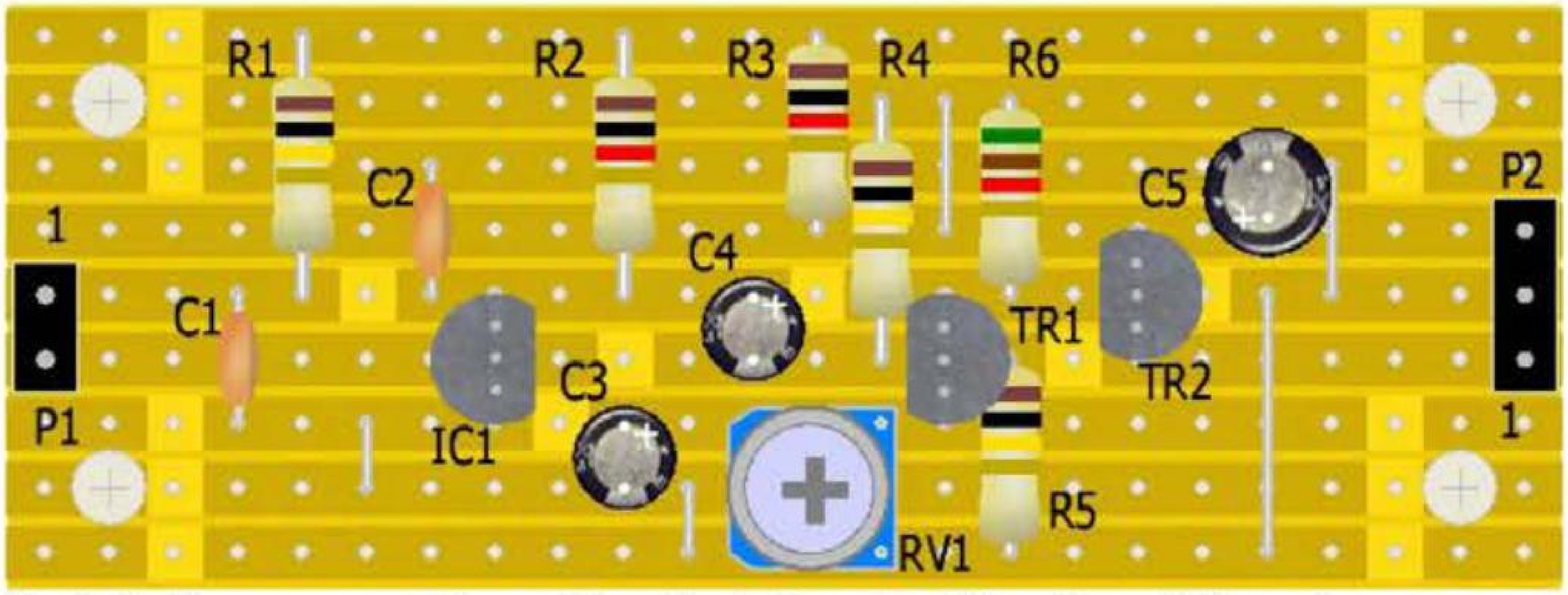


Fig.1.13: the component layout (top view) of our 'crystal set' on stripboard.

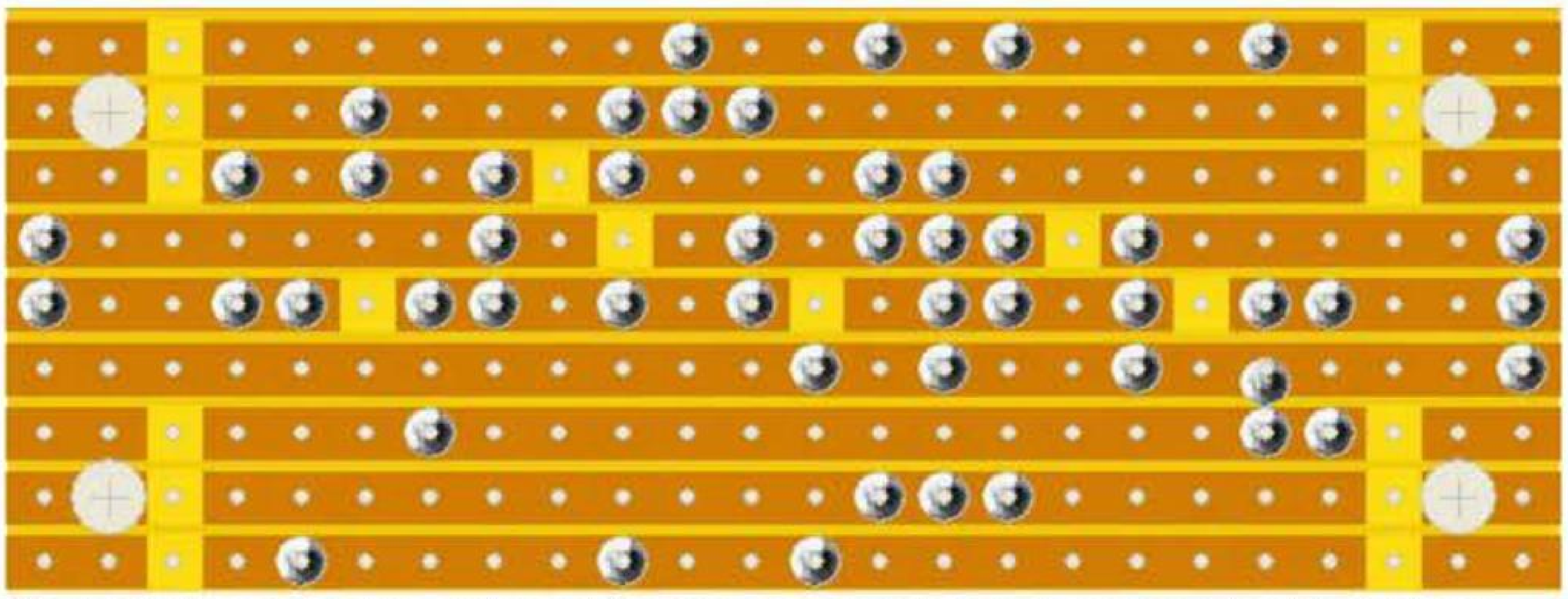
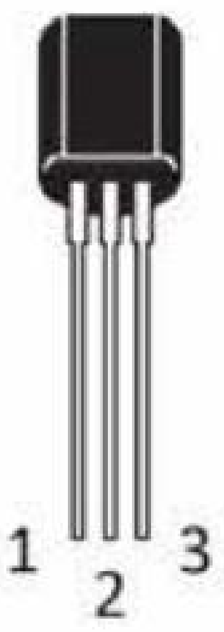


Fig.1.14: the underside of the stripboard, showing the track cuts and soldered leads.



	TA7642	BC548
1	GND	collector
2	IN	base
3	OUT	emitter

Fig.1.15: the pinouts of the semiconductor devices used in the 'crystal set'.

Table 1.4 – Expected voltages

Device	Pin	Voltage
IC1	1	0V
	2	1.26V
	3	1.05V
TR1	C	0.85V
	B	0.74V
	E	0.15V
TR2	C	1.54V
	B	0.85V
	E	0.12V

sufficient gain to amplify low-level incoming signals of a few millivolts or less.

Two external transistor stages contribute additional voltage gain and impedance matching for headphones with a nominal impedance of 32Ω.

The project is constructed on a small piece of perforated copper stripboard measuring 25 × 64mm, arranged as nine strips each of 24 rows. The component layout (viewed from the top) is shown in Fig.1.13, while the corresponding track layout (viewed from below) is given in Fig.1.14.

The required 18 track breaks can be made using a spot face cutter or small drill bit, and the five links on the upper side of the board can be made using short lengths of tinned copper wire. The pin connections for the semiconductor devices are shown in Fig.1.15.

Fig.1.16 shows the finished stripboard module, together with the external tuning components, L1 and VC1. L1 comprises 54 turns of 0.55mm enamelled copper wire close wound over a 70mm length of heatshrink sleeving, into which the ferrite rod is slid. The ends of the winding are secured by PVC tape.

The resulting winding will have an inductance of around 200µH, and with the 270pF variable capacitor, will provide a tuning range from around 700kHz to 1.6MHz.

When completed, the tuning components, switch, headphone connector and battery holder can be mounted in an ABS enclosure of your choice, as shown in Fig.1.17 (we've used a larger enclosure than strictly necessary, as our next Hands-On project can fit in the same enclosure).

Connections to the off-board components (L1, VC1, J1 and S1) are made using the two 0.1" male header connectors (P1 and P2) and short lengths of hook-up wire.

Testing

As always, it's well worth carefully checking the stripboard and internal wiring before applying power. When these checks are complete, connect the headphones and insert a 1.5V battery into the holder. You should immediately hear some noise from the headphones, and a quick sweep of VC1 should reveal several strong broadcast signals.

If that's not the case, remove the battery and re-check the board and wiring. It is also worth checking the headphone connector. For comparison and to assist fault-finding, Table 1.4 provides the test voltages obtained from our prototype.

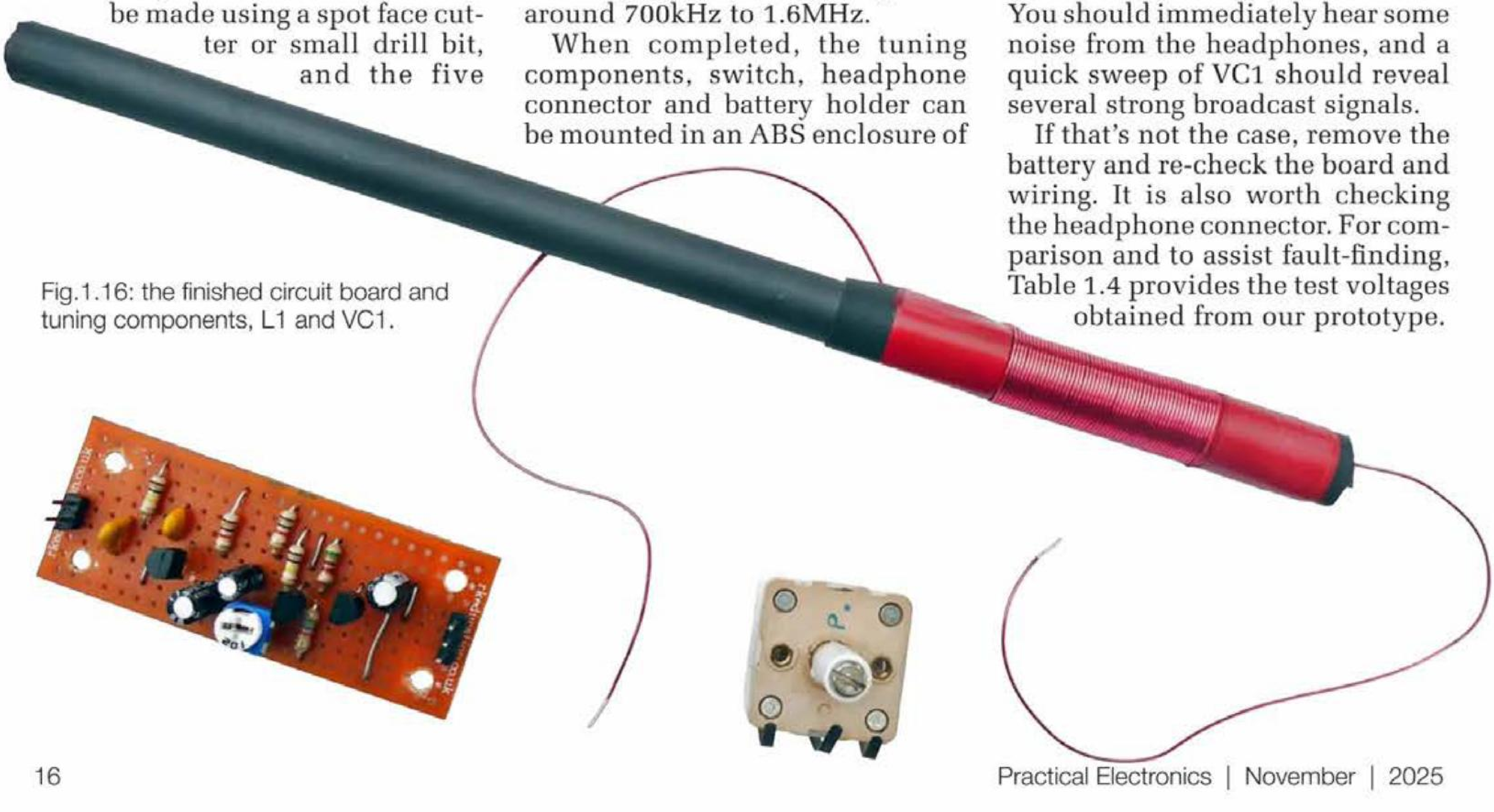


Fig.1.16: the finished circuit board and tuning components, L1 and VC1.

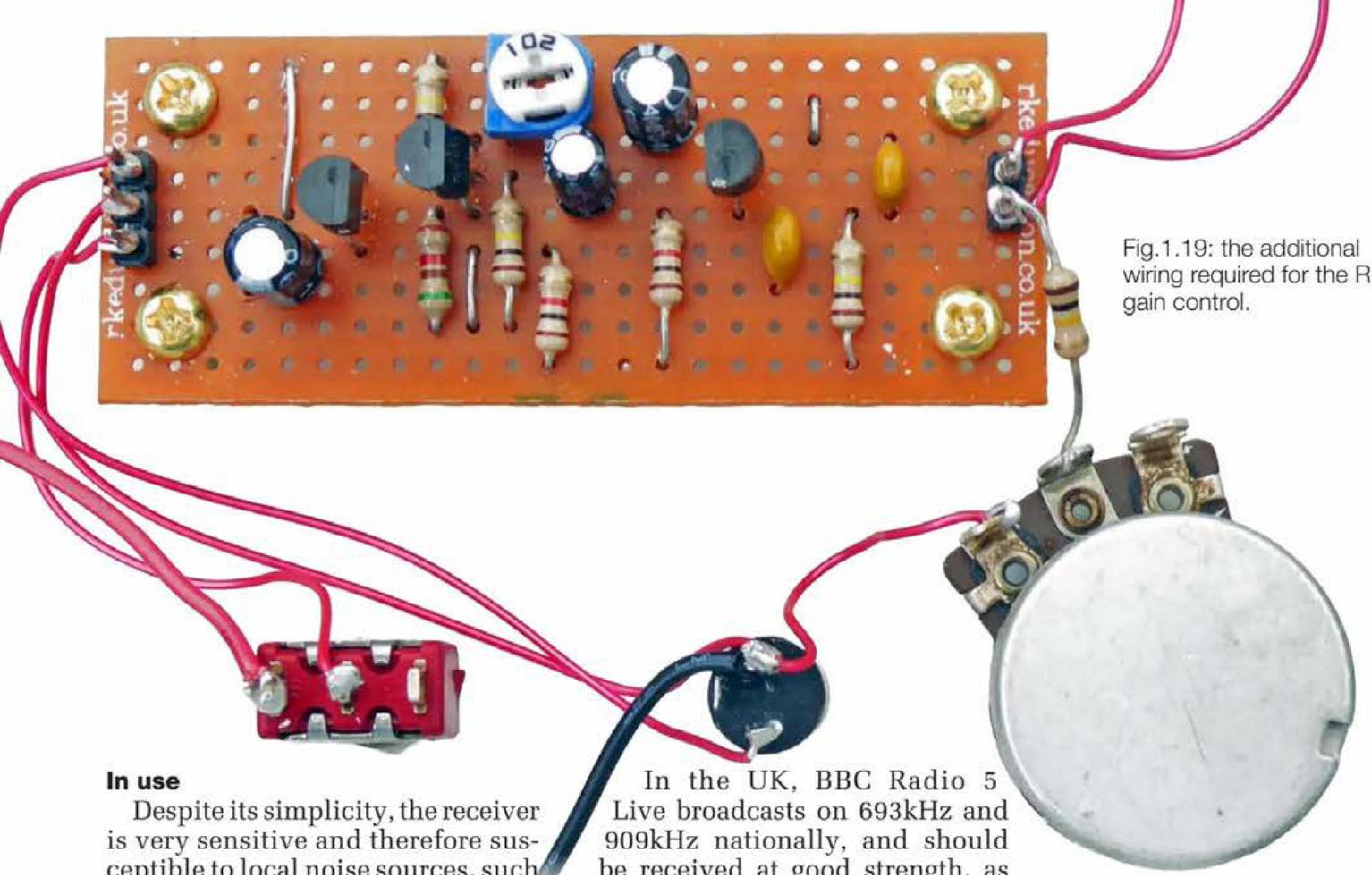


Fig.1.19: the additional wiring required for the RF gain control.

In use

Despite its simplicity, the receiver is very sensitive and therefore susceptible to local noise sources, such as computers, TV receivers and many other electronic devices. For best results, keep the ferrite antenna well away from other devices. The antenna is directional; maximum signal will be obtained when the antenna is side-on to the bearing of the station being received.

These directional properties can be advantageous, allowing you to null or minimise the effects of local noise and interference. Simply rotate the antenna for the least interference and best signal!

During the day, you will normally be able to receive several medium-wave broadcast signals at good strength. More signals will be present during the hours of darkness, and you may also notice some of the ionospheric effects we discussed earlier.

In the UK, BBC Radio 5 Live broadcasts on 693kHz and 909kHz nationally, and should be received at good strength, as will Lyca Radio, which broadcasts on several frequencies from London and Manchester.

TalkSPORT is available on 1053kHz, 1071kHz, 1089kHz and 1107kHz, and provides live coverage of many sporting events, plus news and discussions. With the receiver in a favourable position, all these stations should be received easily.

Adding an RF gain control

When very strong local signals are present, due to the very high internal gain present in IC1, you may sometimes find that our modern crystal set becomes severely overloaded. This can lead to significant audio distortion, but the effect can often be reduced by placing the receiver in a less favourable position or by changing the orientation of the ferrite antenna.

However, if you find this to be a persistent problem, it can easily be resolved by fitting an RF gain control. Fortunately, only two extra components are required for this modification – see Fig.1.18.

The control potentiometer, VR1, should be fitted close to the stripboard (see Fig.1.19). The RF gain can then be adjusted as necessary, but a mid-position setting should prove satisfactory for a wide range of signal levels.

Coming up!

Part 2 of Teach-In 12 will cover RF circuits, components and their underpinning principles. We delve into the constructional techniques required for successfully building radio and wireless equipment. Our Hands-On Project will be an upgraded portable MW AM receiver with a loudspeaker output. PE

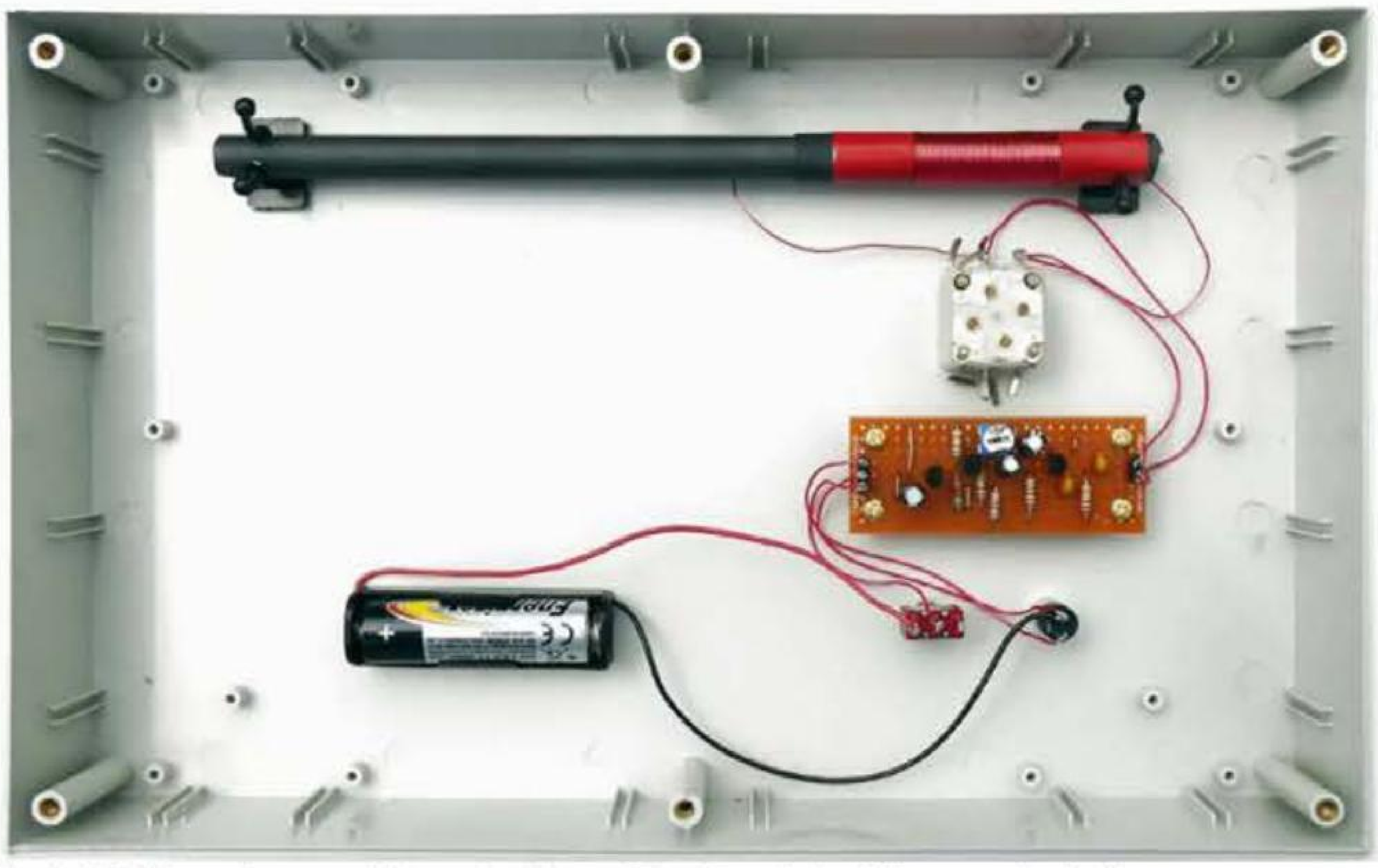


Fig.1.17: internal assembly and wiring of the 'crystal set' in our plastic box.

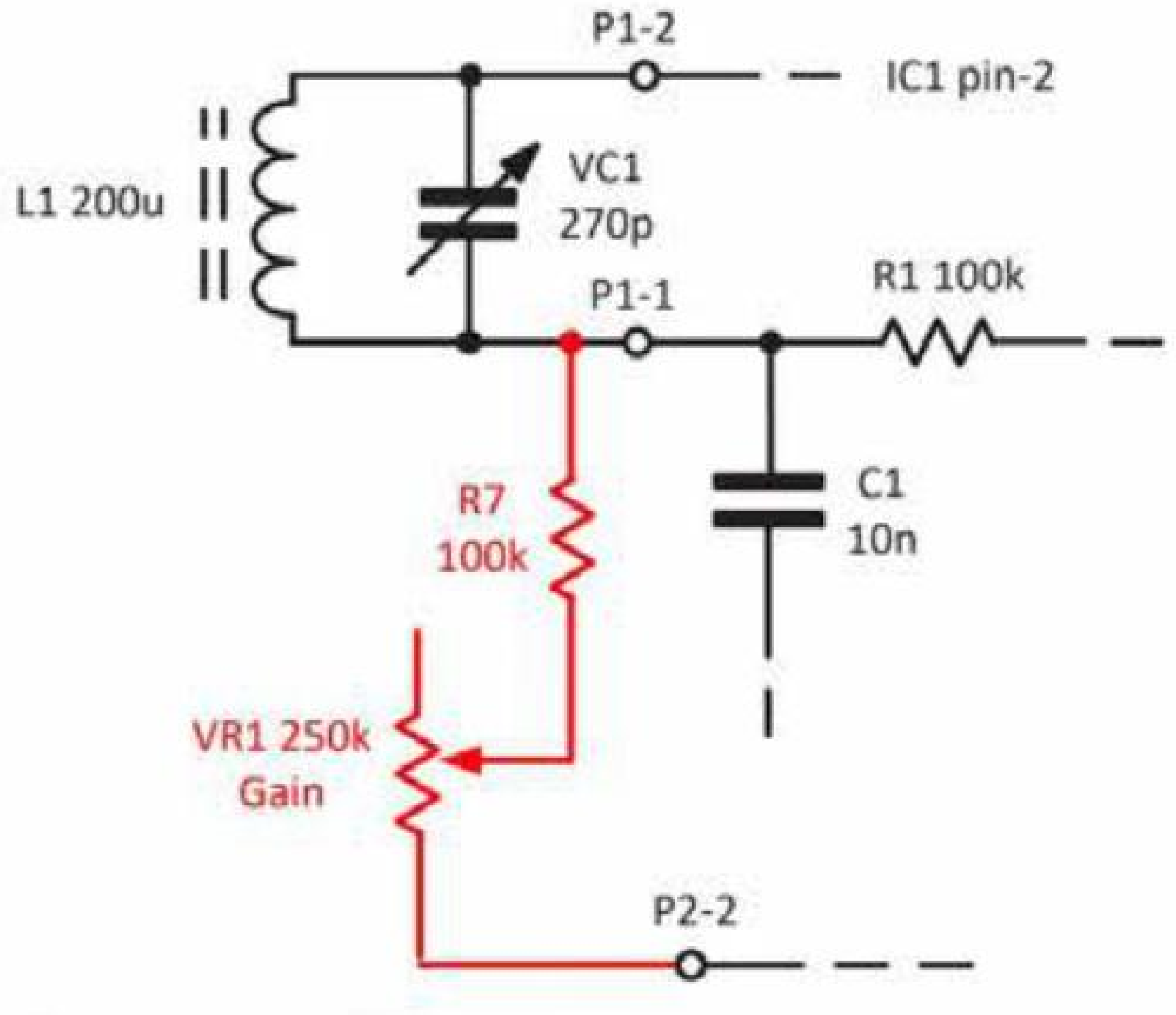
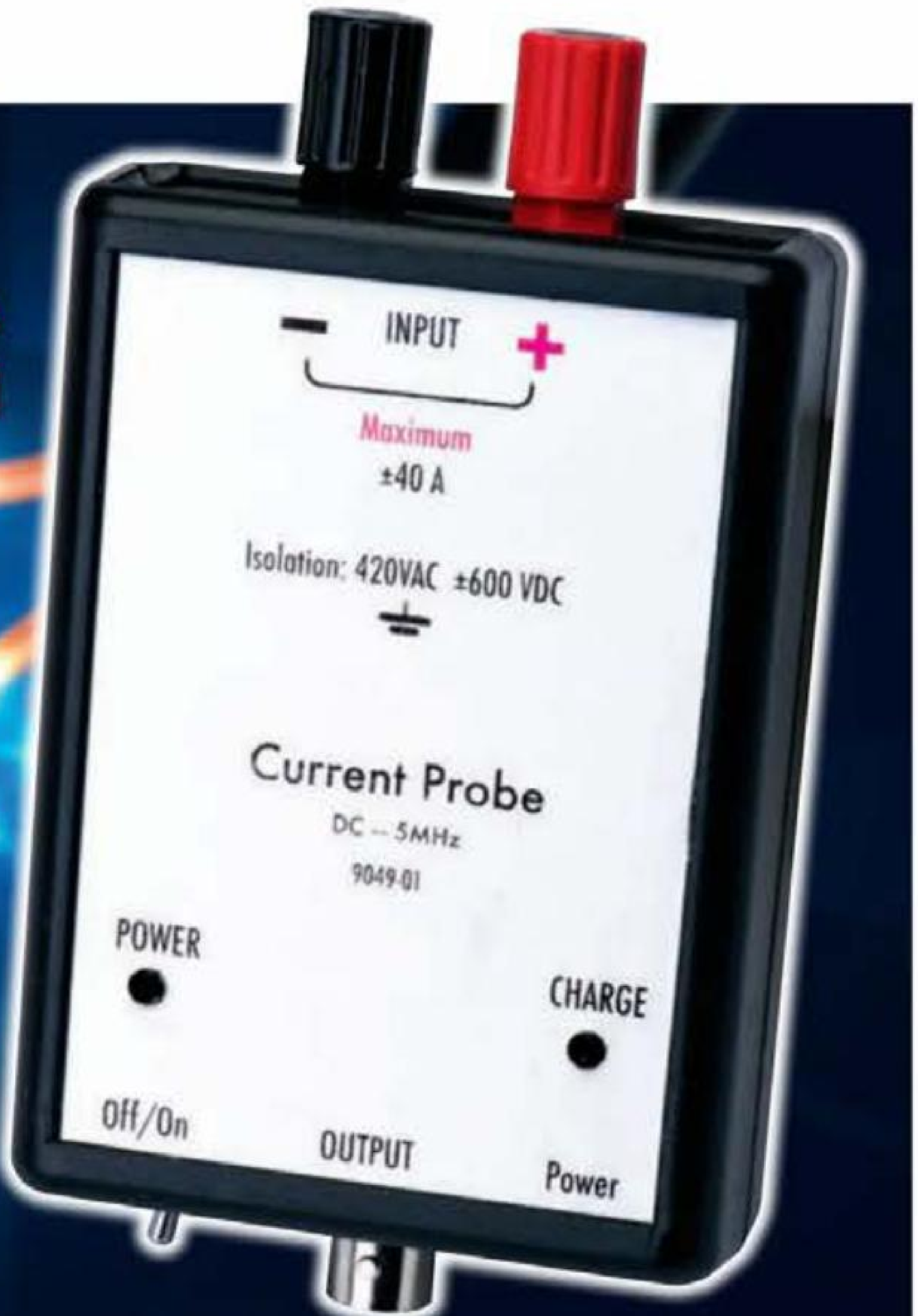


Fig.1.18: an RF gain control can easily be added to the set if it's required.

5MHZ 40A CURRENT PROBE



A current probe is an incredibly useful tool for development, testing and debugging but is usually quite expensive. This DIY version performs well compared to many commercial offerings but at a fraction of the price!

PROJECT BY ANDREW LEVIDO

Using an oscilloscope to monitor the current in a circuit can be challenging. Oscilloscopes are made to measure voltages, so if you can find or add a suitable shunt resistor in the current path, you can measure the current indirectly. However, this is usually only practical at relatively low current levels and only if you can safely connect your 'scope probe ground to one side of the shunt (which is often not the case).

Say there is no suitable shunt resistor, the current runs to several amps or the circuit is not conducive to the safe connection of a grounded probe. You will probably have to use an isolated current probe in those cases. If your circuit operates at mains potential, an isolated probe is mandatory.

You can certainly buy such current probes. The problem is getting good performance at a reasonable price. You can opt to spend thousands of dollars on a high-end 50-100MHz probe from one of the big names in test equipment, or you can spend $100 or less on AliExpress for a no-name probe with a bandwidth of just a few hundred hertz.

I wanted an inexpensive, high-performance current probe, so I built my own. The resulting probe, described here, can measure current up to ±40A, with a bandwidth from DC to 5MHz. Its output is fully isolated from the measurement terminals, so you can safely measure the current of mains-powered devices.

The output, available on a BNC connector, is scaled to 100mV per amp, so it is in the range ±4V. The device is powered by an internal rechargeable lithium-ion cell. Charging is via a power-only USB-C socket.

Scope 1 shows a typical 'scope capture made using the probe. This is the mains inrush current of a variable-frequency motor drive unit, which has a large capacitor bank charged via a bridge rectifier from the mains. A soft-start circuit limits the inrush current at power-on. The vertical scale of the scope capture is 2V per division, corresponding to 20A per division.

You can see that the peak charging current is about 34A in the first half-cycle, with a reduction in the current each cycle after that as the capacitors charge.

Another example capture is shown in Scope 2. Here, a short is applied across a bench power supply set to a 6A current limit. The peak current spikes to almost 50A (showing some headroom in the current probe's design) but rapidly drops as the power supply current regulation circuit begins to operate. Within a millisecond, the current is brought under control and limited to 6A.

Design

The heart of the current probe is the ACS37030 chip from Allegro Microsystems. Like many similar devices, this uses a Hall effect sensor to measure a current indirectly by measuring the magnitude of the magnetic field it produces. See the separate panel for some background on how the Hall

Current Probe Features & Specifications

- Current measurement: bi-directional
- Output scaling: 0.1V/A (±40A translates to ±4V)
- Input/output isolation: 420V RMS (600V peak) 'reinforced'
- Maximum current: 40A peak (35A continuous)
- Bandwidth: DC-5MHz
- Power supply: onboard Li-ion cell
- Battery life: approximately 30 hours
- Charging: USB Type-C socket (5V DC)
- Charging time: approximately 3 hours from flat
- Charging current: 300mA (optionally 100mA)

effect works and how it is used in this application.

Hall sensors are useful in these applications since they work with DC; however, their frequency response is typically limited to a few hundred kilohertz.

The ACS37030 family of sensors is particularly interesting because it pairs a Hall effect sensor for DC and low-frequency signals with inductive sense coils for high-frequency signals. They are available with full-scale current ratings of ±20A, ±40A or ±65A and come in a 6-pin SOIC (small-outline integrated circuit) package with 3500V RMS isolation. All for less than $8 in low quantities.

The block diagram of the ACS37030 is shown in Fig.1. You can see the Hall current sensor at lower left ("Dynamic Offset Cancellation"), with the inductive sensor just above it. The output from the transducers is conditioned by two separate signal chains, which come together at a summing junction. The resulting signal is buffered and offset to produce the output signal.

An advanced digital subsystem uses calibration data stored in non-volatile memory to manage the gain of the two signal paths, providing an accurate output over the whole frequency and operating temperature range.

Since the sensor uses a single 3.3V supply, the output signal swings around a zero-current level of 1.65V, provided by an internal bandgap reference. For the 40A device used here, this output voltage is 1.65V±33.3mV/A for a maximum output swing of just under 0.3V to 3.0V.

Notably, the 1.65V reference is available on one of the pins. Some chips lack such a facility, and it is very difficult to zero them. Even if you have an external trimmable reference voltage that you adjust to get 0V output at 0A current, any differential drift between the two reference voltages will cause the output accuracy to deteriorate significantly.

To display the output voltage conveniently on an oscilloscope, we must remove the offset and amplify the signal to get a ±100mV/A signal based around zero volts. The most straightforward way to achieve this is to use an instrumentation amplifier. An instrumentation amplifier is a high-precision differential amplifier based on op amps that usually uses a single resistor to set its overall gain.

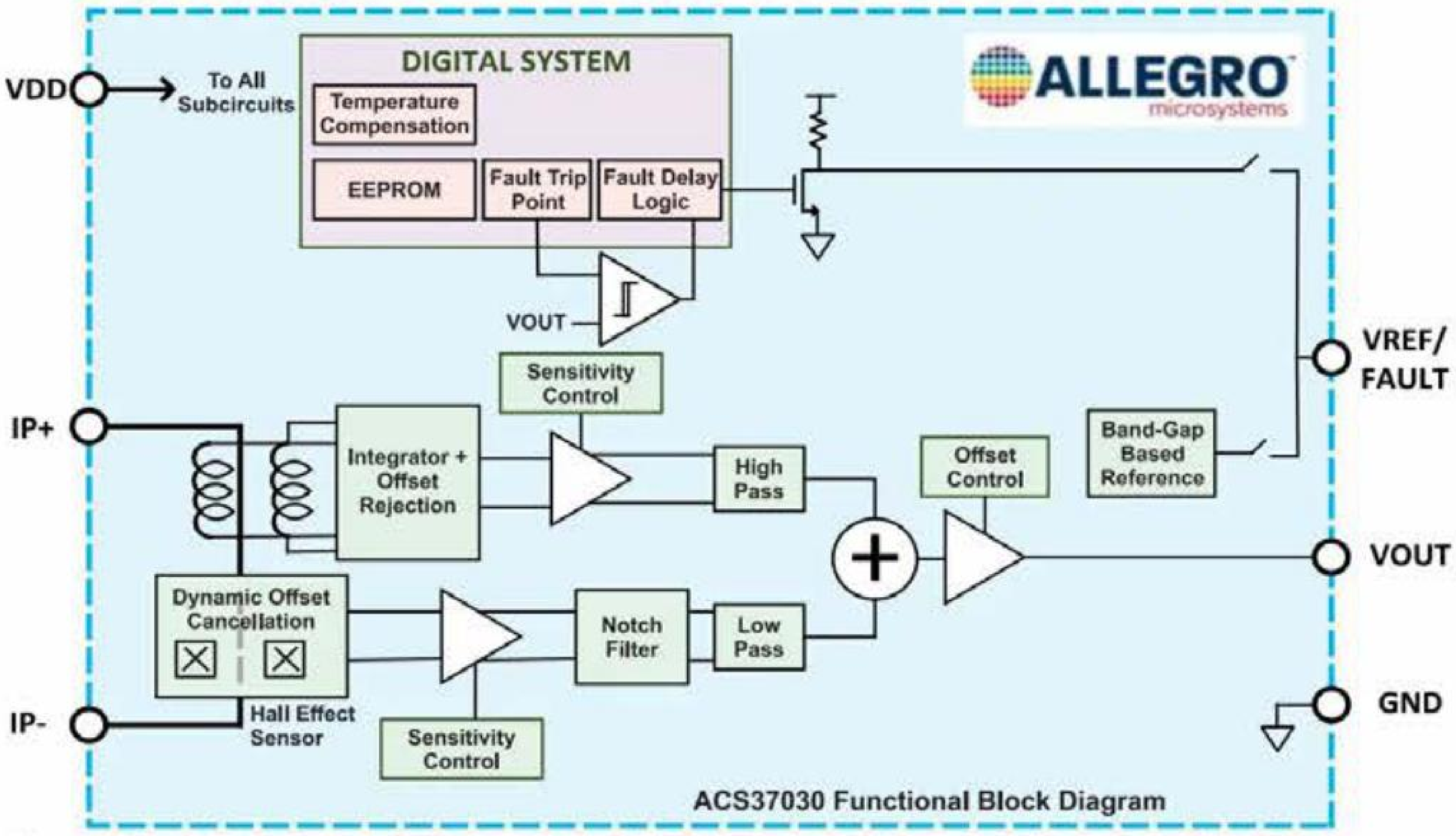
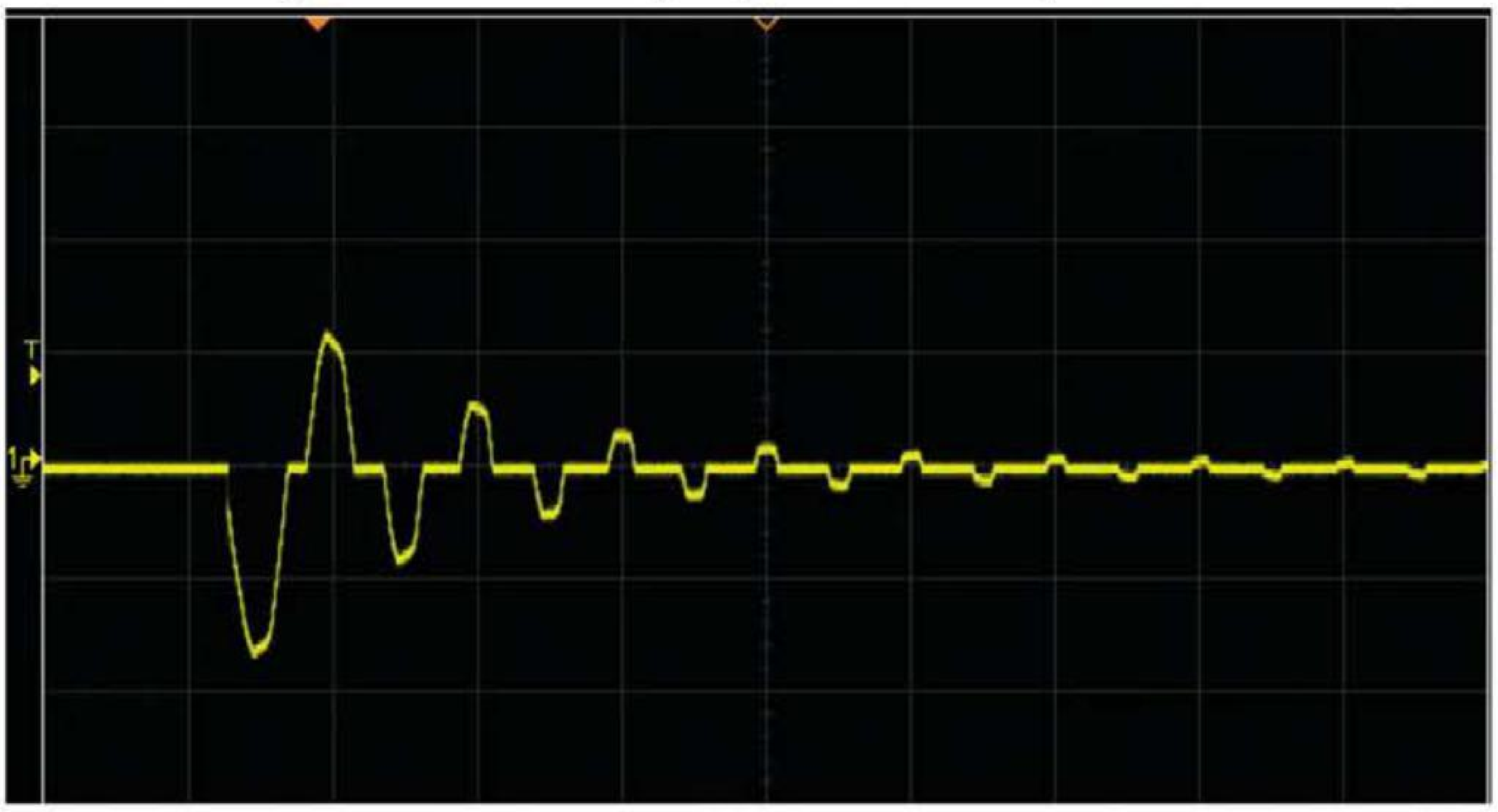
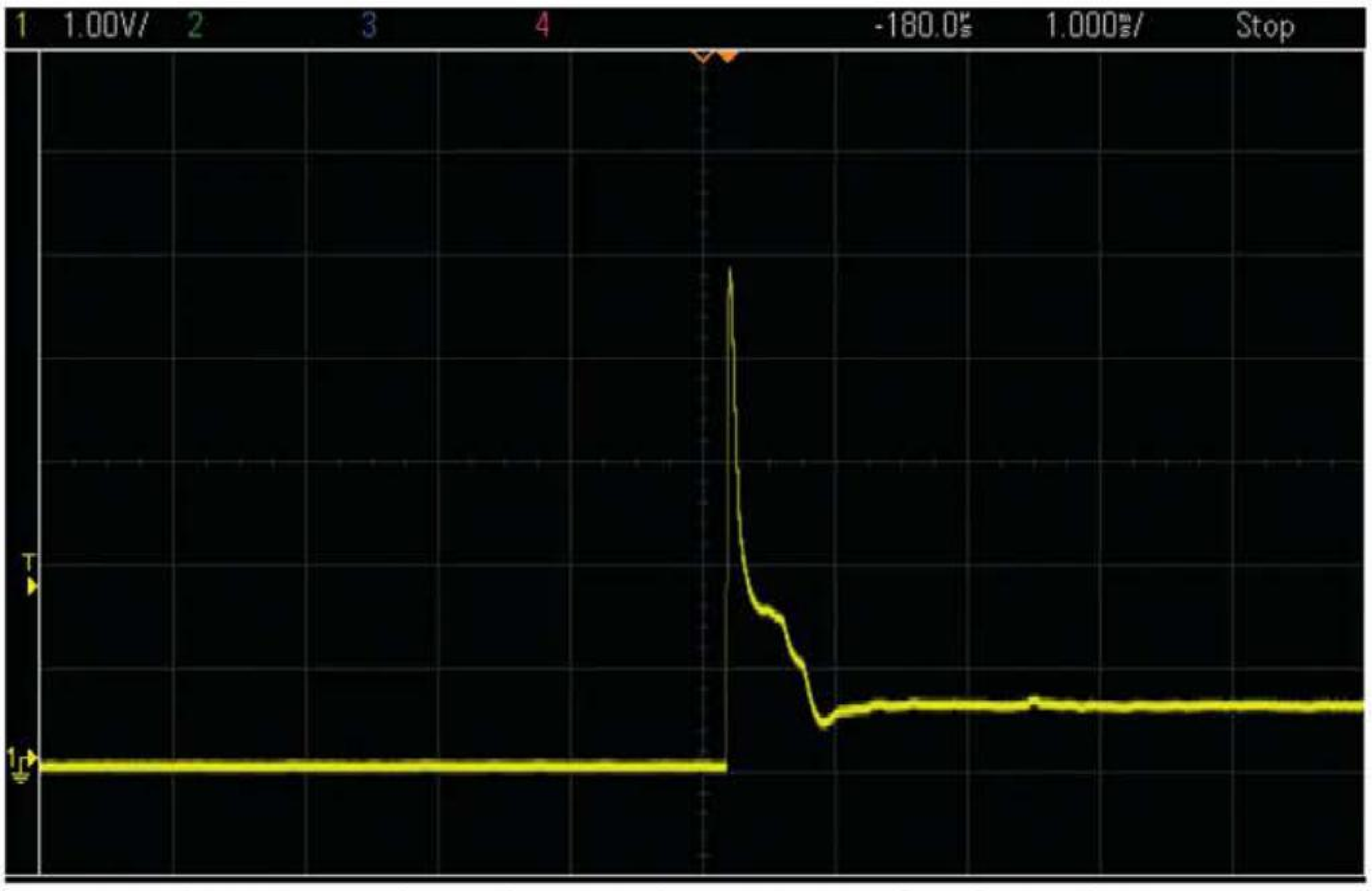

VDD
To All Subcircuits
DIGITAL SYSTEM
Temperature Compensation
EEPROM
Fault Trip Point
Fault Delay Logic
VOUT
ALLEGRO microsystems
VREF/ FAULT
IP+
Sensitivity Control
Integrator + Offset Rejection
High Pass
Offset Control
Band-Gap Based Reference
VOUT
Dynamic Offset Cancellation
Notch Filter
Low Pass
IP-
Hall Effect Sensor
Sensitivity Control
GND
ACS37030 Functional Block Diagram

Fig.1: the ACS37030 current sensor features a Hall sensor for DC and low-frequency measurements, plus an inductive sensor for higher frequencies. These are combined by some clever circuity to provide a flat response from DC to 5MHz.

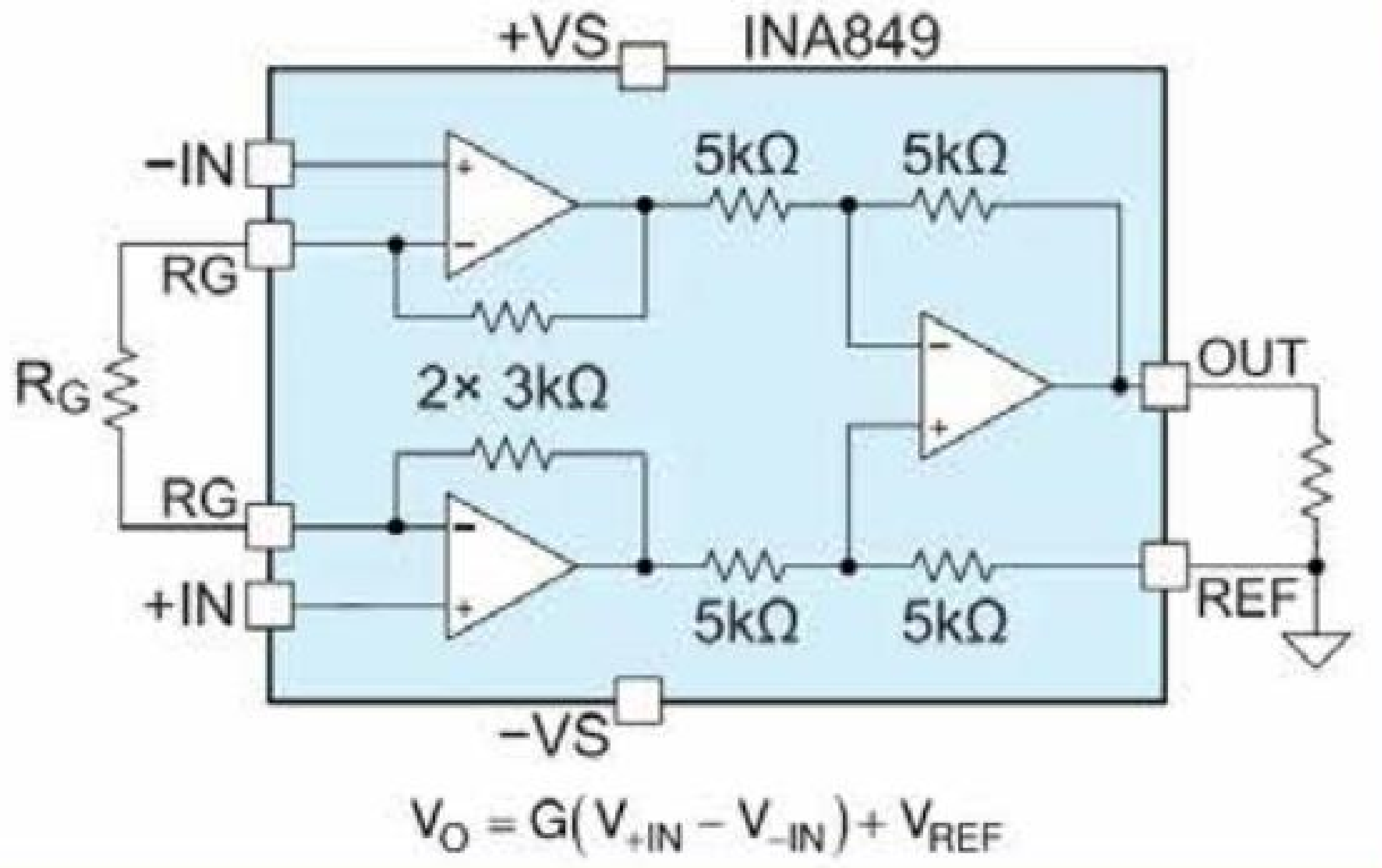


Scope 1: the inrush current for a variable-frequency motor drive as measured by the current probe. The scale is 20A per division.


1 1.00V/
2
3
4
-180.0µs
1.000ms/
Stop
T
1

Scope 2: This scope grab, made using the current probe, shows the current supplied by a short-circuited bench power supply, at 10A per division. The current peaks at almost 50A before being rapidly brought under control and limited to 6A.

Fig.2: the INA849 instrumentation amplifier uses the classic three-op-amp topology with six laser-trimmed matched resistors. One external resistor, R_G, sets the overall gain.


+VS
INA849
−IN
RG
R_G
2× 3kΩ
RG
+IN
5kΩ
5kΩ
OUT
REF
5kΩ
5kΩ
−VS
$V_O = G(V_{+IN} - V_{-IN}) + V_{REF}$

The instrumentation amplifier used in this project is the INA849. It is a classic three-op-amp configuration, as shown in Fig.2. The input stage consists of two non-inverting amplifiers with internal 3kΩ feedback resistors. A single external resistor, R_G, sets the gain of this stage according to the formula $G = 1 + 6k\Omega \div R_G$.

The second stage is a differential amplifier. As the name suggests, it amplifies the difference between two voltages but strongly attenuates any common-mode signal. In the case of the INA849, the differential gain is unity. Therefore, the output voltage is given by the formula $V_{OUT} = V_{REF} + (V_{IN+} - V_{IN-}) \times (1 + 6k\Omega \div R_G)$.

The REF terminal is often connected directly to ground, as per the figure, but you can use it to add an offset to the output if required.

We could build our own instrumentation amplifier from discrete op amps, but it's convenient to use an integrated package like this because the common-mode rejection depends on the close matching of the resistors. Packages like this use internal laser-trimmed resistors matched to a precision that would be difficult (read expensive) to emulate with discrete components.

Circuit details

Now we can turn to the complete circuit diagram (Fig.3) to see how it all works. The ACS37030 (IC1) is powered by a 3.3V rail supplied by low-dropout (LDO) 3.3V linear regulator REG2. The sensor output voltage and the 1.65V reference are applied to the instrumentation amplifier's non-inverting & inverting inputs, respectively.

Achieving a differential gain of three requires a nominal R_G value of 3kΩ. While 3kΩ resistors are available (it's a common E24 value for 1% resistors), I used a combination of fixed resistors plus a trimpot to allow an adjustment range of about ±3% around this figure. This allows the user to trim out any gain error in the sensor, which could be as much as ±2%.

The trimmer has the added advantage of obviating the need for high-precision resistors here.

The ACS37030 data suggests that

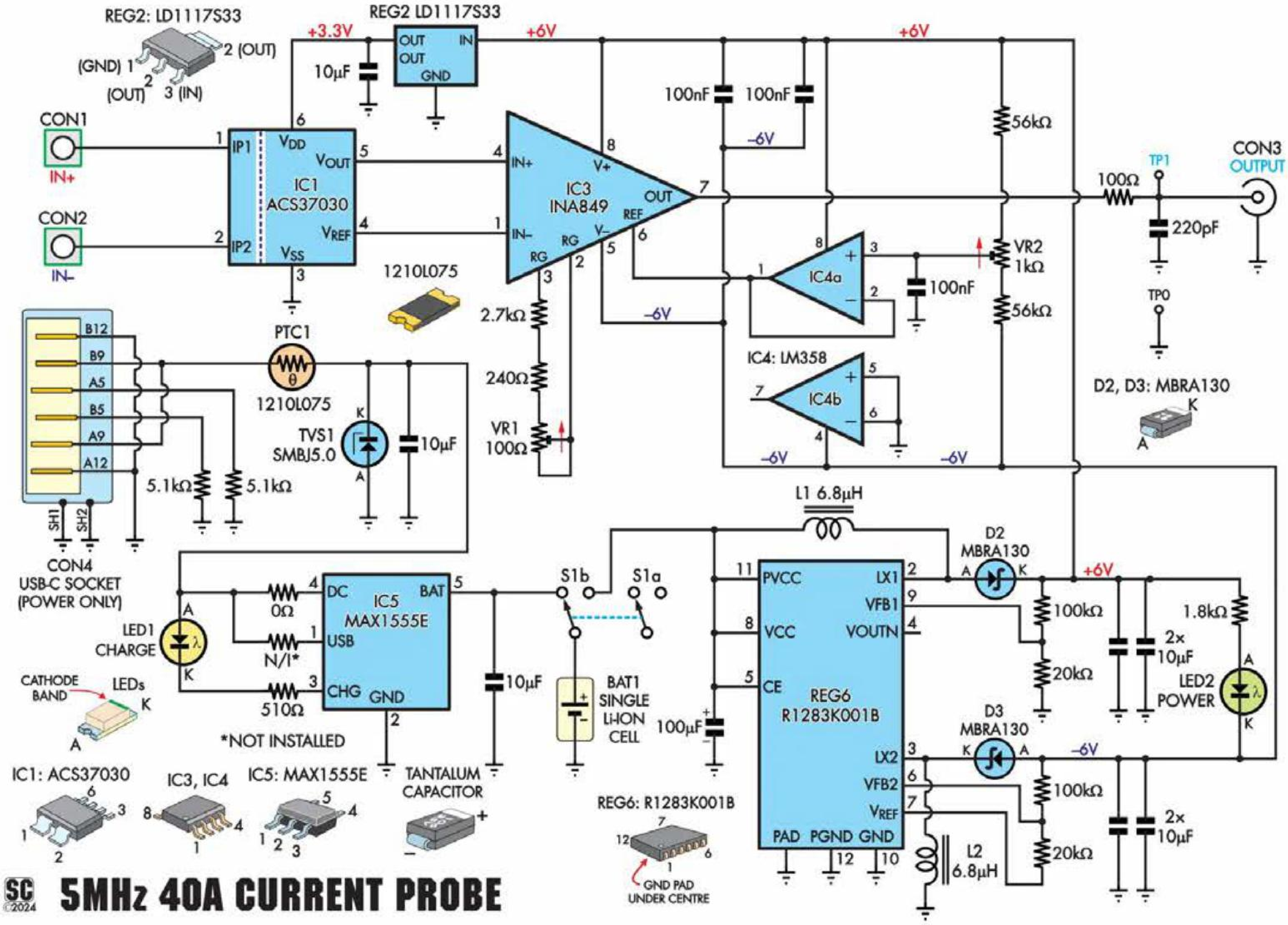

REG2: LD1117S33
(GND) 1
2 (OUT)
(OUT) 2
3 (IN)
+3.3V
10μF
REG2 LD1117S33
OUT
OUT
IN
GND
+6V
+6V
100nF
100nF
−6V
56kΩ
CON1
IN+
CON2
IN−
IP1
IP2
VDD
VOUT
VREF
VSS
IC1
ACS37030
IN+
IN−
V+
V−
IC3
INA849
OUT
REF
RG
RG
100Ω
TP1
CON3
OUTPUT
220pF
TP0
VR2
1kΩ
56kΩ
IC4a
100nF
1210L075
2.7kΩ
240Ω
VR1
100Ω
−6V
IC4: LM358
IC4b
−6V
−6V
D2, D3: MBRA130
K
A
B12
B9
A5
B5
A9
A12
PTC1
1210L075
TVS1
SMBJ5.0
10μF
5.1kΩ
5.1kΩ
SH1
SH2
CON4
USB-C SOCKET
(POWER ONLY)
L1 6.8μH
D2
MBRA130
+6V
PVCC
LX1
VFB1
VOUTN
VCC
CE
REG6
R1283K001B
LX2
VFB2
VREF
PAD PGND GND
100kΩ
20kΩ
1.8kΩ
2×
10μF
LED2
POWER
D3
MBRA130
−6V
100kΩ
20kΩ
2×
10μF
L2
6.8μH
100μF
LED1
CHARGE
DC
USB
CHG
BAT
GND
IC5
MAX1555E
0Ω
N/I*
510Ω
*NOT INSTALLED
10μF
S1b
S1a
BAT1
SINGLE
LI-ION
CELL
CATHODE
BAND
LEDs
IC1: ACS37030
IC3, IC4
IC5: MAX1555E
TANTALUM
CAPACITOR
REG6: R1283K001B
GND PAD
UNDER CENTRE
SC ©2024
5MHz 40A CURRENT PROBE

Fig.3: the current probe circuit reveals that the signal path is very simple, consisting of just the instrumentation amplifier with its associated gain and offset trimming. The balance of the circuit is the power supply and battery charger.

along with the ±2% gain error, there could also be a potential offset error of up to ±10mV. That would translate to ±30mV at the output after amplification. This is why I am driving the instrumentation amplifier's REF pin with an adjustable offset trim voltage of ±50mV derived from the divider that includes trimpot VR2.

The offset trim voltage is buffered by op amp IC4a since the input impedance of the REF pin is relatively low. The instrumentation amplifier's output goes to the output BNC connector (CON3) via a 100Ω resistor to protect the amplifier IC from short circuits at the output.

The rest of the circuit is the power supply. We require a ±6V split supply for the amplifiers. This was chosen because the common-mode input voltage of the instrumentation amplifier can't be any closer than 2.5V from either supply rail. Since our maximum input voltage extends to 3V, we need supply rails of at least ±5.5V. I chose ±6V to provide a bit of headroom.

These rails are derived from a single Li-ion cell via REG6, which contains a boost converter to create the positive rail and an inverting converter to provide the negative rail. The switching Mosfets are internal to the package, but the inductors and rectifier diodes are external: L1/D2 for the positive rail and L2/D3 for the negative.

The output is regulated by providing voltage feedback via two 100kΩ/20kΩ resistive voltage dividers, which reduce the ±6V outputs to ±1V, matching REG6's internal feedback target voltages. The R1283K regulator can operate with an input voltage of 2.5-5.5V, which is ideal for a single Li-ion cell.

When power switch S1 is on, the cell is connected to the DC-to-DC converter. If it is off, the cell is instead connected to IC5, a MAX1555 dual-input Li-ion battery charger. This linear device charges the cell at 100mA if powered via the USB input or 300mA if powered from the DC input.

The USB input is useful for charging from legacy USB hubs, which may not be able to supply more than 100mA. However, this current probe is designed for a USB type-C power source that can supply at least 500mA, so the higher charge current is used to minimise the changing time.

The PCB has provision for either configuration. LED1 will be on while the battery is charging and will switch off once full charge is reached.

The USB-C connector is a power-only type with just a subset of the normal 24 pins. These include the power pins and the control channel (CC) pins, which are terminated with 5.1kΩ resistors to ground. This tells the source that it should supply 5V. The power input is protected from overvoltage by a TVS diode (TVS1) and a series PTC resettable fuse, PTC1.

Construction

All components are mounted on a double-sided PCB coded 9049-01 that measures 56.5 × 76.5mm. The component overlay diagram (Fig.4) shows where everything goes.

To keep it compact, this project uses almost entirely surface-mounted parts. I managed to mostly avoid any difficult-to-handle parts; all passives are M2012/0805 size (2.0 × 1.2mm) or larger and all but one of the semiconductors are in easy-to-solder SOIC-8, SOT-223 or SOT-23 packages.

Unfortunately, the DC-DC converter (REG6) is not available in anything other than a DFN (dual flat no-lead) package, so that is where I suggest you start the assembly process.

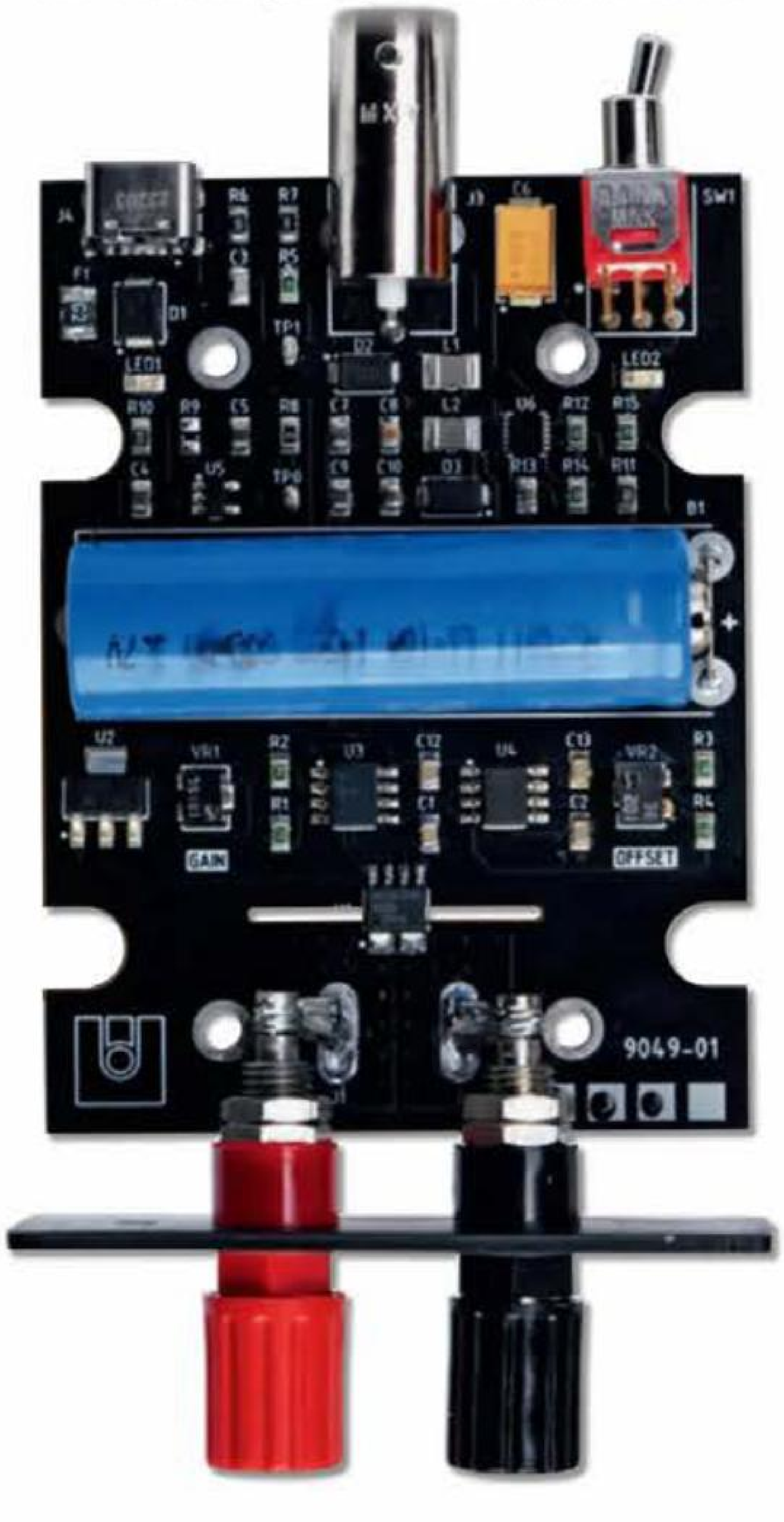
It really helps if you have a hot air reflow station. These stations are useful for soldering chips like this one and also make desoldering many SMDs straightforward. They are not terribly expensive if purchased online.

The easiest way to get REG6 soldered down is to use a soldering iron to lightly tin the pads, including the thermal pad in the centre. The solder should just cover the pads and not be too lumpy. If you put down too much, you can use solder wick to remove the excess.

Next, apply a generous amount of flux paste, position the chip carefully (making sure its pin 1 mark is oriented correctly) and hold it in place with tweezers while you use hot air to gently reflow the solder. Once the solder melts, surface tension should pull the chip neatly into place.

Any visible solder balls or bridges can be removed with solder wicking braid and a hot iron. After cleaning the area with isopropyl alcohol or similar, you have completed the hardest part.

Mount the rest of the surface mount parts using your preferred method. I apply a dab of solder to one pad first, then position the component with tweezers and reflow that pin with the soldering iron. With just one pin soldered, I can tweak the location if necessary to get the other pin(s) into a place I am happy with. Finally, I solder the remaining pin(s). I find this works for two-pin devices like resistors and capacitors, as well as for the ICs.



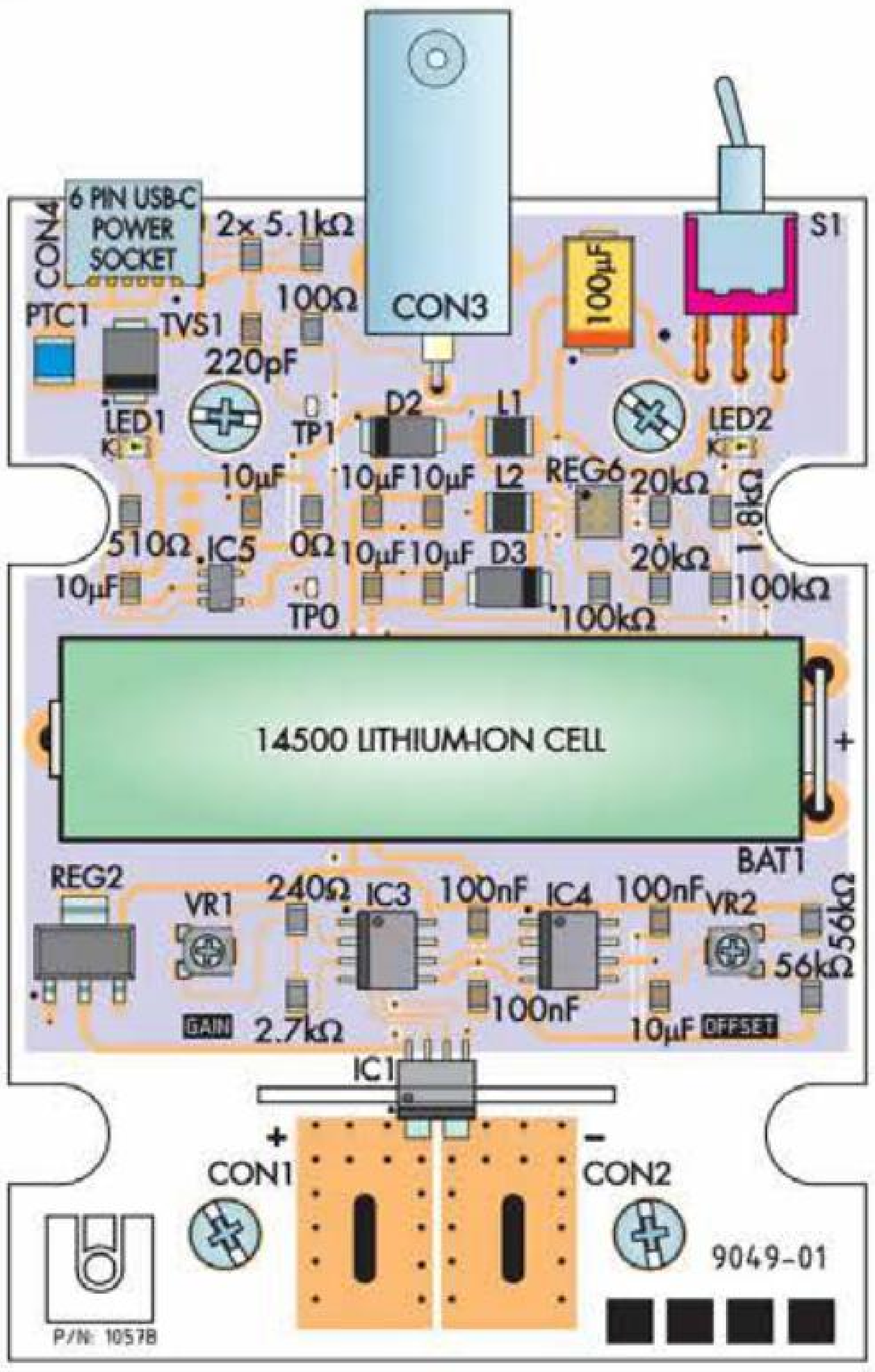


Fig.4: all components are easy-to-solder surface mount or through-hole types, with the exception of REG6. It requires a little more care but is easily achievable for the hobbyist.

Parts List – 5MHz 40A Current Probe

1 ABS handheld instrument case, 92 × 66 × 28mm **[Hammond** 1593LBK**]**
1 double-sided PCB coded 9049-01, 56.5 × 76.5mm
1 14500 (AA-size) Li-ion cell with solder lugs (BAT1) **[eBay** 357385477329**]**
2 6.8μH 1A SMD inductors, M3225/1210 size (L1, L2)
  [Murata 1276AS-H-6R8M=P2**]**
1 0.75A 24V PTC fuse, SMD M3225 size (PTC1) **[Littelfuse** 1210L075/24PR**]**
1 100Ω 4.9 × 3.9mm SMD trimpot (VR1) **[**SM-42TW101**]**
1 1kΩ 4.9 × 3.9mm SMD trimpot (VR2) **[**SM-42TW102**]**
1 PCB-mounting sub-miniature DPDT toggle switch (S1)
  [E-Switch 200MDP1T2B2M6RE**]**
1 red panel-mounting binding post (CON1) **[Cal Test Electronics** CT2232-2**]**
1 black panel-mounting binding post (CON2) **[Cal Test Electronics** CT2232-0**]**
1 right-angle PCB-mount 50Ω BNC socket (CON3) **[Molex** 0731000105**]**
1 USB type-C power-only socket with through-hole mounting pins (CON4)
  [Molex 217175-0001 **or equivalent]**
2 panel-mount 3mm light pipes, 15mm long (for LED1 & LED2)
  [Dialight 51513020600F**]**
2 Koa RCUCTE SMD test points (TP0, TP1; **optional**)
4 No.4 × 6mm self-tapping screws
1 100mm length of 1.0-1.5mm diameter tinned copper wire

Semiconductors
1 ACS37030LLZATR-040B3 5MHz 40A current sensor, SOIC-6 (IC1)
1 LD1117S33 or equivalent 3.3V 800mA LDO regulator, SOT-223 (REG2)
1 INA849DR 28MHz instrumentation amplifier, SOIC-8 (IC3)
1 LM358 dual single-supply op amp, SOIC-8 (IC4)
1 MAX1555EZK-T Li-ion battery charger, SOT-23-5 (IC5)
1 R1283K001B-TR buck/boost switching regulator, UFDFN-14 (REG6)
1 yellow SMD LED, M2012/0805 size (LED1)
1 green SMD LED, M2012/0805 size (LED2)
1 SMBJ5.0CA 5.0V TVS diode, DO-214AA (TVS1)
2 30V 1A schottky diodes, DO-214AC/SMA (D2, D3) **[**MBRA130LT3G, SS14**]**

Capacitors *(all SMD M2012/0805 50V X7R unless noted)*
1 100μF 25V tantalum, SME case **[Kyocera** TAJE107K025RNJ**]**
7 10μF 16V
3 100nF
1 220pF C0G

Resistors *(all SMD M2012/0805 ⅛W 1% unless noted)*
2 100kΩ
2 56kΩ
2 20kΩ
2 5.1kΩ
1 2.7kΩ
1 1.8kΩ
1 510Ω
1 100Ω
1 240Ω
1 0Ω

INPUT
–
+
Maximum
±40 A
Isolation: 420VAC ±600 VDC
Current Probe
DC – 5MHz
9049-01
POWER
CHARGE
Off/On
OUTPUT
Power

With the switch to the right, the probe is powered; to the left, it can be charged via USB.

The current sensor chip, IC1, straddles an unplated slot cut into the board. This slot is to provide plenty of creepage distance between the current being measured and the rest of the circuit. However, it makes the board quite flexible in this area, so handle it carefully after soldering IC2. If the board is flexed too much, it is possible to overstress the IC's pins and break them – as I unfortunately discovered!

Solder the USB connector's through-hole tabs first to locate it, then the six smaller surface-mounting pins.

Case preparation

Before you fit the BNC connector, binding posts or battery (well, cell), it's a good idea to prepare the case. That will allow you to align those larger connectors properly. The cell should be left off until the testing described below is completed.

Drill the enclosure's cover and end plates as shown in Fig.5. The USB slot can be made by drilling two 2.8-3.0mm holes at either end and then filing out the plastic between them.

Now drop the PCB into the case, resting on its mounting bosses, insert the BNC connector through the hole in the end plate and drop it into its mounting holes on the PCB. If everything lines up, you can tack-solder the BNC connector in place from the top, then remove the whole assembly from the case and solder it properly, taking care that it doesn't bend as you do so.

If it doesn't fit perfectly, you will need to enlarge the panel hole slightly and try again.

Now attach the input terminals (binding posts) to the appropriate end plate and tighten the nuts. Connect the input terminals to the PCB using a few lengths of tinned copper wire bent over the terminal studs, through the PCB slots, and soldered in place. Remember that this connection could carry up to 40A, so ensure it is solid.

Remove the assembly from the case and trim off any excess wire. Make sure that there cannot be any shorts between the terminals!

Testing

If you have a current-limited bench supply, it's a good idea to test the circuit before soldering the cell to the board. Set the onboard switch to the on position, towards the BNC connector. Set the bench supply to 4V with a limit of around 100mA. Then, taking care to connect it with the correct polarity, hold its output leads to the two battery pads and monitor the current draw.

The power supply should not go into current limiting; the circuit should only draw about 20-30mA. LED2 (green) should light. If all seems well, you can disconnect the power supply, switch off the onboard power switch and solder the battery in place. If something is wrong, check all your soldering carefully and verify that all components are installed correctly.

Before soldering the cell to the PCB, make sure the power switch is in the off (charging) position, with the toggle switch away from the BNC connector. Once the cell is installed, treat the board with care. Inadvertently shorting things now could be catastrophic, as Li-ion batteries can source a lot of current.

We used a PCB-mounting cell but they are unfortunately quite hard to find, so we suggest instead you source a cell with small solder tabs, like the one in the parts list, then attach it to the pads with short, stiff wires (be careful to get the polarity right!).

Check that the cell voltage is 3.0-4.2V. Switch the unit on, and LED2 should light again. Check for 6V across the 10μF capacitor immediately to the left of L2 and the similar capacitor immediately to the left of D3. That will verify that both supply rails are correct.

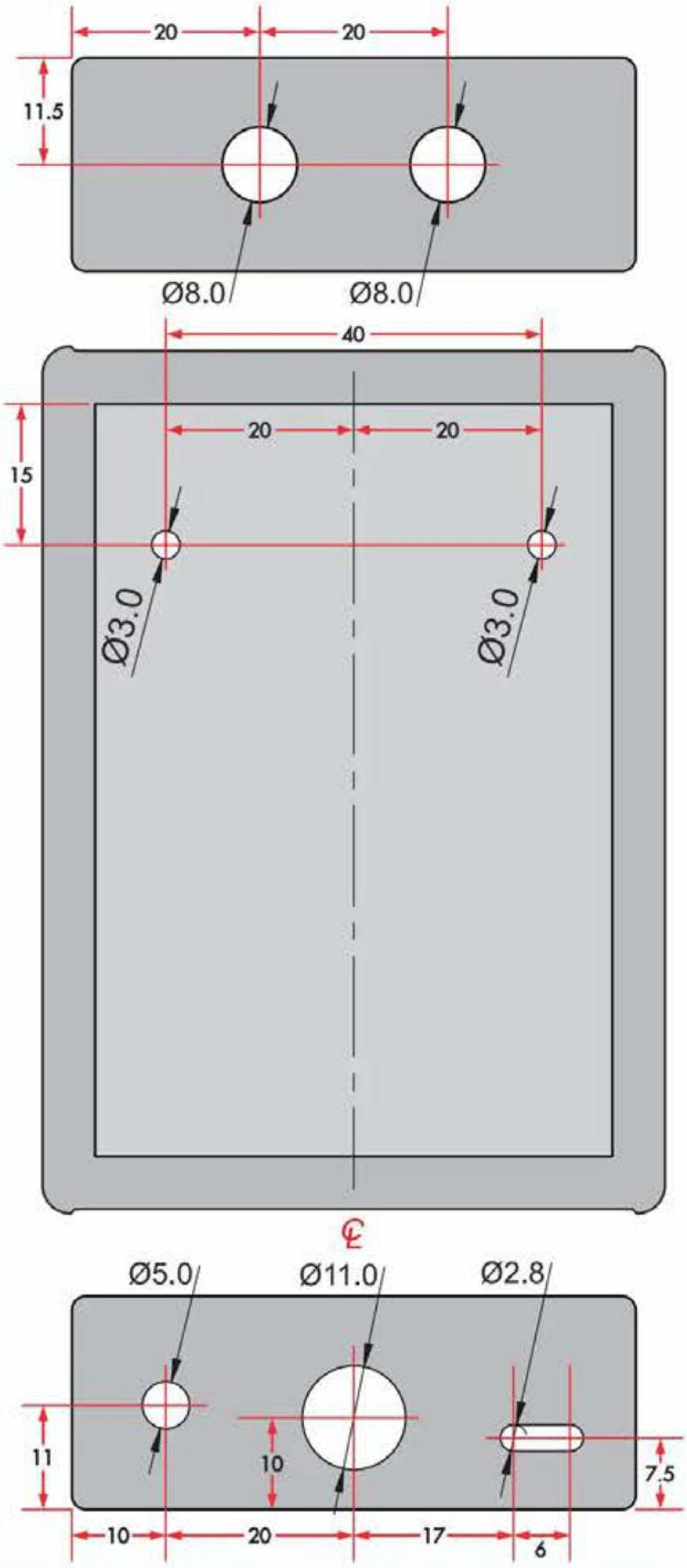
If the readings are wrong, switch it off immediately; you most likely have a problem with the power supply section. Check REG6 and its surrounding components, especially L1, L2, D2 and D3.

Once the power supply is working correctly, you can check the battery charging circuit by switching the unit off and connecting a suitable USB supply. The yellow charge LED (LED1) should light, and the voltage across the battery should begin to slowly rise.

When the battery voltage reaches about 4.2V, the charge LED should go out, indicating that the battery is fully charged. Depending on the battery's initial state of charge, that could take a few hours.

Final assembly

You can now apply the front panel label, shown in Fig.6 (download from siliconchip.au/Shop/11/490).



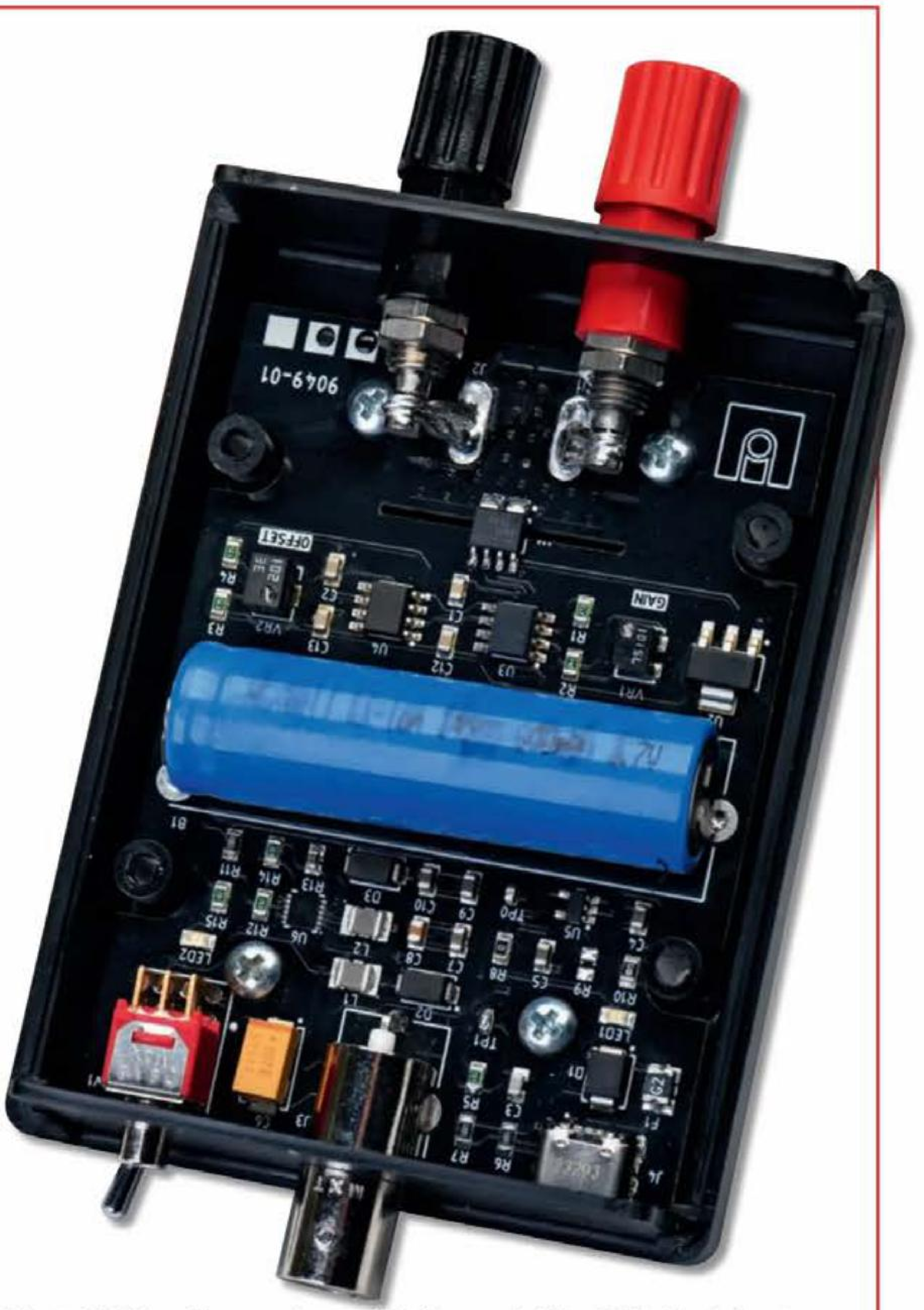


Fig.5: drilling the case is straightforward. The USB slot is best made by drilling two 2.8-3.0mm holes at the ends and joining them with a file. You can see how the finished case looks at left, and how the PCB slots into the case shown enlarged above.

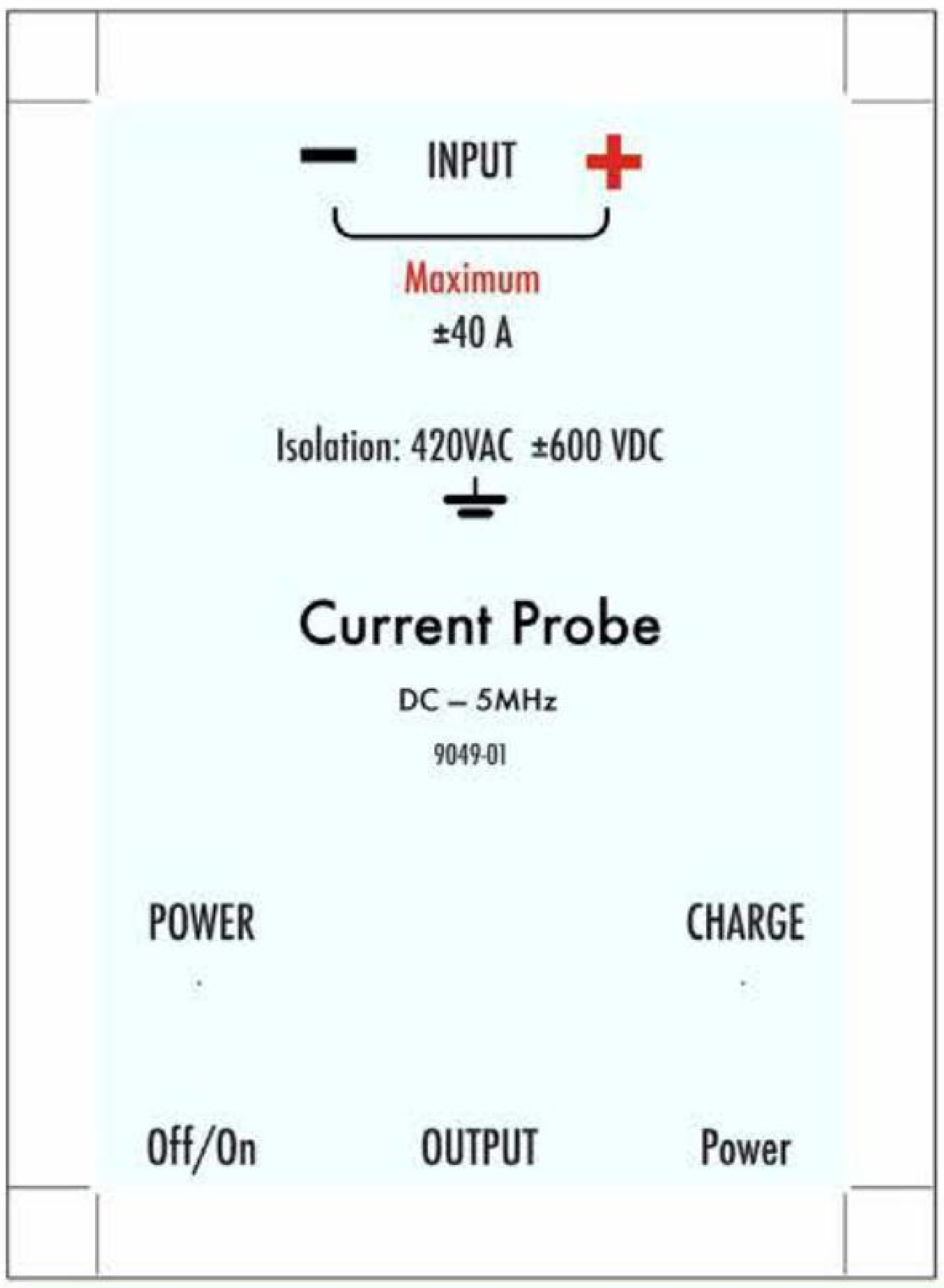


Fig.6: the label artwork for the front of the enclosure. Print it on sticky-backed paper, cut out the outline and apply it (or laminate it, or use your preferred label-making method). Use the case as a template to cut the holes for the light pipes.

Once it is in place, carefully cut out the LED holes and insert the light pipes from the outside. They can be secured with a drop of cyanoacrylate (super) glue on the inside of the case.

Slip the end plate over the BNC connector, switch and USB socket and screw the whole assembly into the base of the enclosure with 6mm self-tapping screws.

Calibration

To calibrate the Probe, you will need a current-limited bench power supply capable of sourcing a few amps and a multimeter. If you have two meters, so much the better. First, set the offset trim.

Connect the meter, switched to a low voltage range, between the probe output test point (TP1) and ground (TP0). With the unit switched on and nothing connected to the input terminals, adjust the offset pot (VR2) for a meter reading close to 0V. You should be able to get it to less than ±1mV.

To trim the gain, configure the power supply to deliver a few volts and set the current limit to 3A or whatever maximum your power supply will deliver. Switch your meter to read current (remember to swap the probes to the correct jacks), select the appropriate range, and connect it across the power supply.

The supply should go into current limiting and regulate the current somewhere near the setpoint. Record the current value displayed on the meter.

Now switch the meter back to volts and connect it back to TP0 and TP1 as before. Connect the current probe inputs across the power supply without changing any of the settings. The output voltage should read close to one-tenth of the current reading you noted earlier.

For example, if you measured the current to be 3.02A, you should see something like 0.302V on the meter. If the reading is a bit off, adjust the gain pot VR1 to get it as close as possible.

If you have two meters, you can measure the input current and output voltage at the same time (the current meter goes in series with the probe across the power supply). That will be a bit more accurate (and easier) than switching the meter around.

Using it

Due to the high currents that the probe can handle, probes (alligator clip wires etc) should not be used unless both the voltage and current are low (under 50V DC/AC & 5A).

For higher voltages/currents, you can cover the exposed wires that are attached to the binding posts with heatshrink.

As there is exposed metal on the binding posts, if any voltage above 50V is applied to the Probe, that end of the device must be considered live. Position the Probe so that nobody can come in contact with that end, and also to keep the isolated measurement end away from any high-voltage wiring. The Probe itself has a high isolation, but you must ensure that isn't degraded by any external shorting hazards. **PE**

The Hall Effect

Edwin Hall first described the Hall effect in 1879, just a decade after Maxwell published his seminal work on the interaction of electric and magnetic fields. The lower left diagram shows how it works.

A current (green arrow) flows through the long axis of a conductor that is subject to a magnetic field perpendicular to the direction of current flow (lavender arrow).

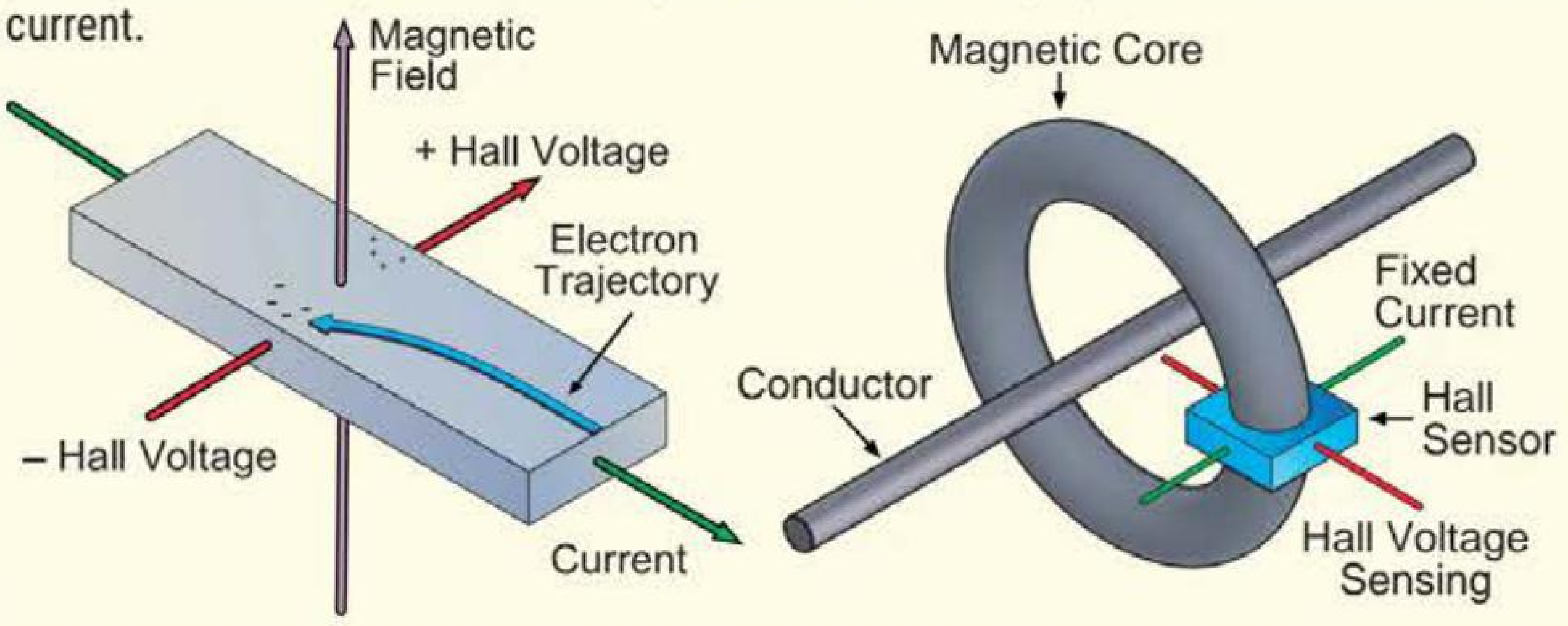
Hall discovered that under these circumstances, the electrons making up this current – which flow in the opposite direction to the current – would experience a Lorentz force pushing them towards one side of the conductor, as shown by the curved blue arrow.

As a reminder, Lorentz's law states that a charged particle, such as an electron, moving in a magnetic field will experience a force at right angles to both the direction of the field and its velocity. This is the basic principle by which electric motors and generators work.

The build-up of negative charge on one side of the conductor (and the corresponding positive charge on the other side, where there will be a dearth of electrons) produces an electric potential across the conductor. This Hall voltage is proportional to both the conductor current and the strength of the magnetic field.

The Hall effect also works in semiconductors, although the polarity of the Hall voltage may be different in some semiconductors where 'holes', rather than electrons, are responsible for current flow.

In practical Hall effect sensors, the current to be measured passes through a conductor surrounded by a magnetically permeable core. The Hall sensor is positioned in a narrow gap in this core, so the magnetic field produced by the current in the conductor passes through the element perpendicular to both the excitation current and the Hall voltage measurement terminals. Since the excitation current is fixed, the Hall voltage is proportional to the magnetic field strength, which is, in turn, proportional to the conductor current.



AOShop

The home for specialist audio, analogue and historic components – provided by Jake Rothman, *PE's Audio Out* columnist. The AOShop is your best bet for classic analogue 'NOS' (new old stock) components, including all parts for *Audio Out* projects and designs.

Ge semiconductors

Small-signal PNP transistors	
NKT214F, OC57, OC59, 2N1377, 2N525	**£1.00**
Low-noise PNP transistors	
GET106	**£2.50**
Small power PNP transistors	
AC153, AC153K, AC188	**£1.50**
Small power NPN transistors	
AC176, AC141K	**£2.00**
High-voltage PNP transistors	
OC77, CV7001	**£1.50**
TO3 PNP power transistors	
OC22, CV7054 (OC23), OC25, OC35, OC36, AD143, AD149, AD161, AD162	**£2.00**
AD140	**£3.50**
AD149, AD161/2 matched pair	**£5.00**
RF PNP transistors	
OC41, OC42, 2SA12, 2SA53,AF124, AF178, GET872A	**£1.50**
NPN transistors	
OC139, OC140, ASY73	**£2.00**
Diodes	
CV7049 (OA10), CG92 (OA91)	**£0.50**

Si semiconductors

Diodes	
ZC5800 RF Schottky	**£0.20**
Low-noise silicon transistors	
BFW16A, 2SC3071, 2SC3068, 2SA1016K, 2SC2362K, 2SA970BL	**£1.50**
2SC2204, 2SD655, BC550C	**£0.50**
ZTX651	**£0.30**
ZTX751	**£0.50**
RF transistors (suitable for Theremin)	
BF199	**£0.50**
Audio power MOSFETs	
Exicon 10N20, 10P20	**£6.50**
Hitachi 2SJ99, 2SK343	**£3.50**
Hitachi 2SJ56, 2SK176	**£8.50**
JFETs	
BFW11, BFW10, TIS73L, J177, J113, U1994, U1898, 2SJ176, J201	**£1.00**
J175, J176, J112, J111, 2N3820, 2N5467, BF244, 2N5460, J230	**£0.60**
Small power output/driver transistors	
2SB649A, D669A, 2SA1208, 2SC2910, MJE253G, MJE243G, 2SA1725, 2SC4511	**£1.20**
BD139,BD140, BD135, BD156, BD435, BD436, MPSA63, BCV46	**£0.50**
MOSFETs	
ZVP2106A	**£0.30**
Dual-gate 3SK45, BFS28	**£1.50**
Metal-cased transistors	
BCY71	**£0.30**
Amplifiers	
LM318 high-speed op amp	**£0.35**
µA709 metal-cased op amp	**£2.00**
5534H metal-cased op amp	**£3.00**
LM384, TDA2030A, TDA2050V	**£1.50**
TAA435 (Mullard power amp driver for AD161/AD162)	**£1.20**

Synthesiser ICs

That/dbx 2180 VCA/VCF	**£6.00**
CA3080 VCA/VCF (vocoder)	**£2.80**
CA3280 VCA/VCF	**£4.00**
LM13600/ LM13700 VCA/VCF	**£2.00**
CA3086 transistor array	**£1.00**
PT2399 echo/delay	**£1.50**

Dual transistors

2N2639, 2N2223, 2N2910 (NPN)	**£4.00**
E401 (JFET Moog)	**£4.00**
2SK2145-Y dual JFET	**£0.80**
2N5564 JFET	**£8.00**
HN3C51F, HN3A51F	**£1.00**
DMMT3904/6, HN1A01F, HN1C01F	**£0.50**

Loudspeakers

PE Mini-Monitor	
Volt PE165 6.5-inch woofer (each)	**£85**
Morel MDT29 tweeter (each)	**£25**
Kit *pair* of PE165/MDT29 plus Volt crossover parts and PCBs	**£299**
Monacor DT-28N tweeter (each)	**£35**
Vifa 19mm BC20SC15-04 tweeter (each)	**£15**
Volt crossover inductors	
1.2mH, 1.5mH, 2mH, 2.7mH, 0.5mH (tapped at 0.3mH) (each)	**£5.85**
Fully assembled and tested high-quality speaker prototypes – ask for details	
LS3/5As and other similar speaker systems (pair)	**£200-£350**
Fully tested reclaimed speakers	
Vifa BC14 5-inch woofer (each)	**£10**
Vifa TC26 1-inch tweeter (each)	**£10**
Low-price speakers	
Philips 4-inch 4070	**£2.00**
EMI 10x6-inch, 30Ω Alnico	**£7**
64mm 64Ω neodymium	**£1.20**

Capacitors

Note '10/63' denotes '10µF 63V'.

Polyester	
3.3/100, 4.7/250, 4.7/63	**£1.00**
5.6/63, 8.2/63, 10/63	**£2.00**
Mullard 'Mustard' C296 0.22/400	**£2.00**
Polycarbonate	
Axial 2.2/63 1%, 4.7/160, 6.8/63	**£1.00**
Radial	
6.8/160V, 10/63	**£2.00**
Reclaimed 22/63	**£2.00**
Polystyrene	
Philips 1% 4.7nF/160, 6.2nF/500, 12nF/63, 22nF/63, 110nF/63, 24nF, 2nF	**£1.00**
RIFA 1% 100nF/100, Suflex 90.9nF 0.5%	**£2.00**
Suflex 2.5% 10nF/63 (rad. or ax.)	**£0.50**
Radiation resistant	
Siemens cellulose acetate MKL 2.2/25	**£0.80**
Electrolytic – Mullard blue 017 series	
10/25, 22/25, 100/10	**£0.50**
150/40, 470/40, 1000/40	**£1.00**
Tantalum – axial metal cased	
22/50, 47/35, 68/25, 100/20, 120/10, 150/16, 220/10, 330/6	**£2.00**
22/35, 33/35, 47/20, 68/15, 100/10, 150/6	**£1.25**
4.7/50, 6.8/35, 10/25, 10/35, 22/15	**£1.00**
Axial moulded-case tantalum	
Kemet axial 6.8/10	**£0.30**
Kemet radial 33/10	**£0.40**
STC radial 100/20	**£1.50**
Tantalum bead	
22/50	**£1.00**
470/3	**£2.00**
680/6.3	**£3.00**
Wet tantalum	
220/25 axial	**£3.20**
Castanet button 140/30, 470/3	**£3.20**
Hughes 540/10	**£3.20**
Bipolar	
Hermetic bipolar tantalum 16/35	**£3.20**
Elcap axial 10/50	**£0.50**
Generic radial 100/16, 470/35, 100/ 63, 22/35, 4.7/35, 220/16	**£0.50**
Philips solid-aluminium (axial) 121/123	
47/16	**£1.00**
330/6.3	**£2.00**
100/35	**£4.00**
Philips Pearl 122 series (radial)	
10/16	**£0.30**
Silvered mica (radial)	
1nF/500 1%	**£1.00**
Trimmer capacitors	
Vishay plastic-film 4-40pF	**£0.80**
Vishay plastic-film 5.5-45pF	**£1.00**
Vishay plastic-film 5-80pF	**£1.20**
Vishay plastic-film 10-250pF	**£2.00**
Mica 1-12pF, 2-40pF	**£1.00**

Audio transformers and inductors

Eagle transformers	
LT44, LT722 driver, LT700, LT723 500Ω output	**£2.50**
LT30 500mW output	**£3.50**
5:1 interstage (fuzz box)	**£1.50**
Repanco	
T/T3 splitter transformer	**£4.00**
CH2 5mH RFC	**£2.00**
Balanced output transformer	
Vigortronix 600Ω VTX-101-007	**£10**
Vigortronix 600Ω VTX-101-3001	**£10**
Vigortronix 600Ω VTX-101-3002	**£15**
Gardners 150Ω	**£10**
Reclaimed BBC LL74/MPC nickel core 600Ω	**£12**
Low-level 1:1 600Ω (modem)	**£2**
Reclaimed mic input transformer	**£15**
Inductors	
82µH, 4.7mH, 100µH, 270µH, 10µH, 14µH (low Z)	**£0.50**
7-inch ferrite rod with MW and LW windings	**£3.00**

Special resistors

Bourns wire-wound trimmer 5kΩ 3059 JM panel-mount	**£2.00**
Thermistor RA53, R13	**£4.00**
A13	**£2.00**
Thermistor CZ1, CZ6	**£1.50**
Holco H2 2.2MΩ 1W, 1%	**£1.00**
Welwyn 1GΩ 2W	**£1.00**
5k Bourns 3321H cermet trimmer	**£0.50**

Potentiometers

Bourns 81	
25kΩ lin cermet	**£2.00**
25kΩ lin, 5kΩ lin cond. plastic	**£3.00**
Bourns 91	
10k dual-gang lin or log	**£10.00**
Plessey moulded-track	
5kΩ log with switch	**£3.00**
50kΩ A/log	**£3.00**
Mil 250kΩ lin dual	**£5.00**
Alpha	
16mm 4.7kΩ A/log	**£0.80**
220kΩ A/log	**£0.80**
10kΩ lin centre-detent dual-gang	**£1.50**
Allen Bradley J series/Honeywell	
10kΩ lin 1 million cycles	**£5.00**
Blore Edwards AB 45 dual 5kΩ A/log with switch	**£3.50**
Alps RK9 dual-gang 5kΩ RD law	**£4.00**
Alps 50k log tapped motor. stereo	**£5.00**
BI P260 500kΩ log conductive plastic 1 million cycles	**£2.00**
Colvern wire-wound 100kΩ or 50kΩ dual-gang 3W	**£5.00**
Mil Spec hermetic 10Ω	**£8.00**

Miscellaneous

PCBs	
Fuzz Box (*PE*, Nov '25)	**£3.00**
Dual JFET Buffer (*PE*, Oct '25)	**£2.00**
Mosfet Buffer (*PE*, Oct 2025)	**£2.00**
Dual Mosfet Buffer (*PE*, Oct '25)	**£2.00**
Cascode Amp (*PE*, Sep 2025)	**£2.00**
Cascode PS (*PE*, Sep 2025)	**£2.00**
Pocket Theremin (*EPE*, 1996)	**£2.00**
Elysian Theremin (*EPE*, 1996)	**£6.00**
Synth VCF, VCO (*EPE*, 2017)	**£3.00**
48V PSU (*EPE*, 2019)	**£3.00**
SMT dual transistor adapter	**£0.40**
Relays	
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MAX'S COOL BEANS

By Max the Magnificent

WEIRD & WONDERFUL ARDUINO PROJECTS

Part 11: connecting the console's 7-segment displays

After all sorts of interesting discussions about boolean logic and such over the last few issues, it's time for the other shoe to drop. I fear we've dillied and dallied in recent columns, meandering our way through a morass of teasingly tempting topics.

You may well wonder if we've lost sight of our original goal, which is to construct a retro games console that will be the object of desire and the envy of all who see it (see Photo 1). "No!" I cry, "A thousand times no!"

In this column, we will take the first tentative steps toward adding the 7-segment displays at the top of the console's front panel (visible at upper left in Photo 1). In next month's column, we will complete this process and also (hopefully) add the eight push-button switches at the bottom of the console's front panel (at lower right in Photo 1).

Initially, we will connect all these components directly to our Arduino Uno to make sure everything functions as planned.

Holding it together

I'm hoping that, like me, you're working with a laser-cut front panel. I'm also hoping that, in the fullness of time, you plan on mounting this panel in a custom 3D-printed enclosure.

However, if you don't have access to a laser cutter and a 3D printer (or a well-equipped friend), you can always attach everything to something like a piece of hardboard (aka pressboard), or ¼-inch (6.35mm) thick plywood and call it a prototype.

Always remember that a hot glue gun is a tool of champions. That said, never apply hot glue to electronic components while the circuit is powered, as the heat can cause damage or even trigger thermal runaway in sensitive devices. I learned this the hard way several years ago with some tricolour LEDs in Adafruit NeoPixel rings. I won't do that again.

One step at a time

One of the lessons we've (hopefully) learned during our time together is that when we're working on a new circuit, or moving from one version to the next, it's almost always better to change just one thing at a time. This is one of those engineering wisdom things that applies to the prototyping and debugging of both hardware and software.

Why? Well, if we tweak a bunch of things at the same time, and whatever we're working on starts to misbehave, we won't know exactly what caused the problem. That can send us down a rabbit hole of time-consuming guesswork.

Alternatively, if we take things step by step, every change teaches us something. We'll spot problems immediately, avoid breaking something that was already working, and develop a better understanding of how our hardware or software behaves. Working this way might feel slower in the moment, but it saves a ton of time (and frustration) in the long run.

Taking our first step

Thus far, we've been using a 74HC595 8-bit serial-in, parallel-out (SIPO) shift register as part of our breadboard-based experiments (Fig.1).

Different data sheets may refer to the outputs from this device as **a** to **h**, **A** to **H**, **QA** to **QH**, or **Q0** to **Q7**. In our case, we may switch between referring to things like "bit 0", "output 0" or "output a", depending on what works best in the given context.

As a brief reminder, the shift register device contains two 8-bit registers. We refer to one of these as the 'shift register' (which can be a

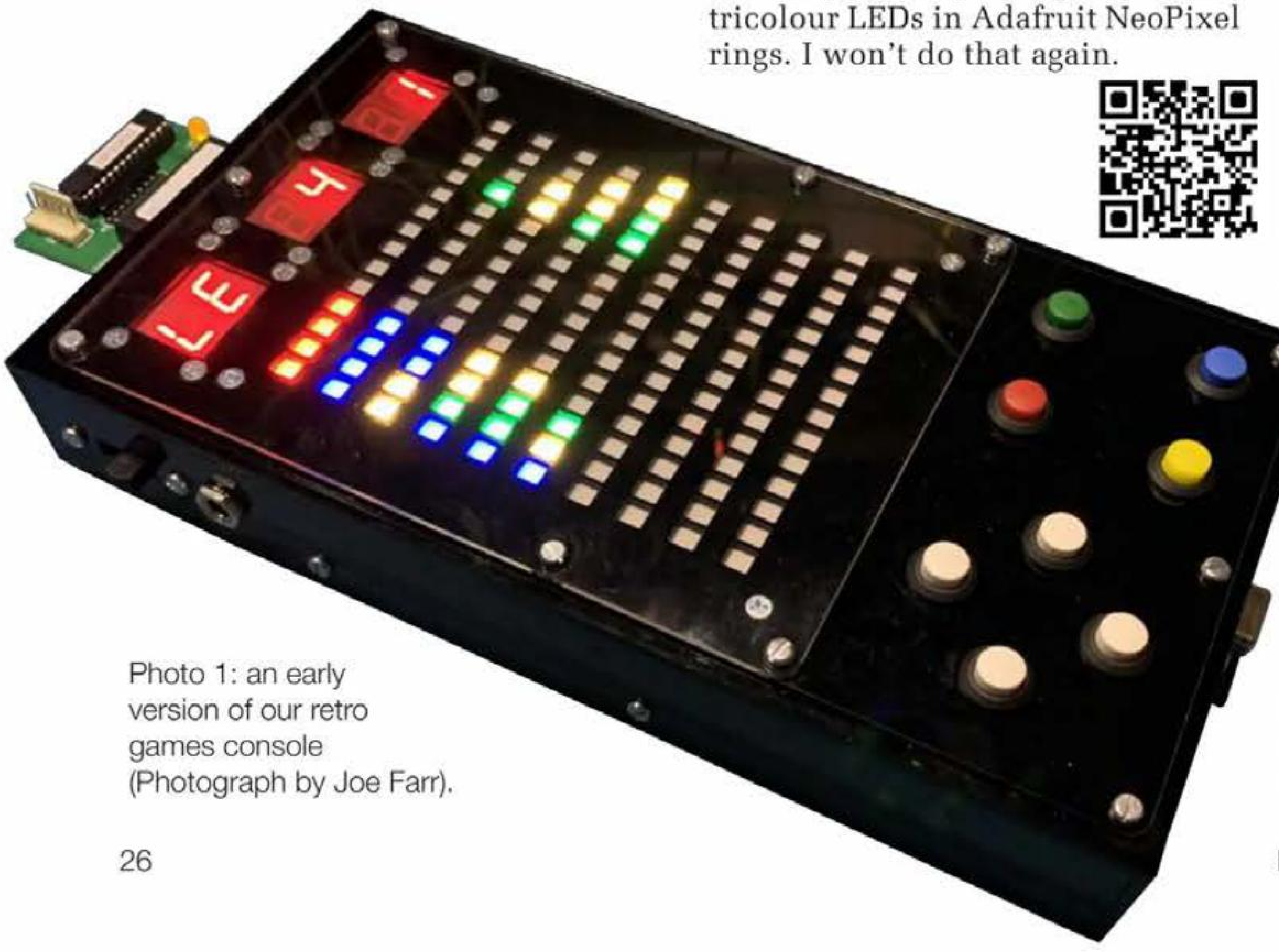
Photo 1: an early version of our retro games console (Photograph by Joe Farr).

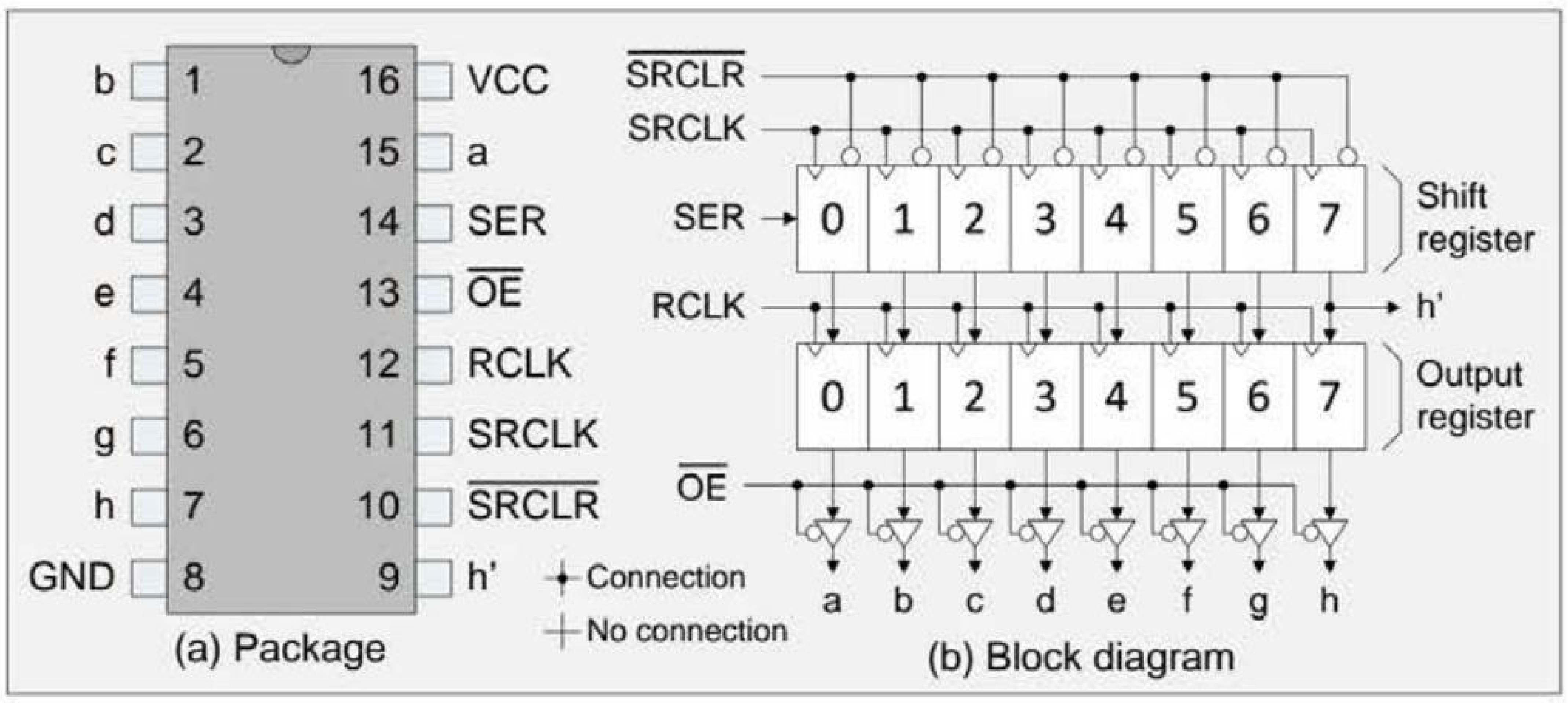

Fig.1: the pinout and internal structure of a 74HC595 serial-to-parallel shift register.

tad confusing), and the other as the 'output register'. The operation of this component can be summarised as follows.

A logic 0 on the active-low **$\overline{\text{SRCLR}}$** (shift register clear) input loads all the bits in the shift register with 0.

A rising 0 → 1 transition on the positive-edge-triggered **SRCLK** (shift register clock) input causes the contents of the shift register to be shifted one bit (to the right in this illustration).

Whatever 0 or 1 value that's currently on the **SER** (serial data in) input is copied into bit 0. At the same time, the original contents of bit 0 are copied into bit 1, the contents of bit 1 are copied into bit 2, and so on down the line. The original contents of bit 7 conceptually 'fall off the end' (or form the input to the next shift register device in the chain).

A rising 0 → 1 transition on the positive-edge-triggered **RCLK** (output register clock) copies all the bit values in the shift register into the corresponding bits in the output register.

Finally, a logic 0 on the shift register's active-low **$\overline{\text{OE}}$** (output enable) input allows whatever values are stored in the output register to be made available on the 74HC595's output pins. By comparison, applying a logic 1 to this input causes the output pins to be placed in a tri-state (high-impedance) condition, effectively disconnecting the output buffers from the outside world.

It's important to note that the **$\overline{\text{OE}}$** signal does not affect the values stored in the output register, only the values visible to the outside world.

By some strange quirk of fate, the 74HC595 is the same device (albeit in a smaller, surface-mount package) that's featured in the display modules we're going to add to our games console, but we're going to do a few things differently from them.

For example, thus far, we've been taking advantage of the active-low **$\overline{\text{SRCLR}}$** input to clear our shift register. However, the creators of the display modules have not made this signal available to us. This means that when we wish to clear the device, we will need to shift in a series of 0 values.

Additionally, we began our experiments by connecting the **SER** input to logic 1. Later, when we implemented a Johnson counter, followed by a linear feedback shift register (LFSR), we used the output from another logic device to feed the **SER** input. Now, we're going to drive this input directly from our Arduino.

In our most recent experiments, we used Arduino digital input/output (I/O) pins 5, 6, and 7 to drive the shift register control inputs **$\overline{\text{SRCLR}}$**, **SRCLK** and **RCLK**, respectively. This made sense at the time, but this pin group is slap-bang in the middle of the digital pins. Since we are soon going to be using all of these pins, that's a tad inconvenient.

First, we'll remove all the extraneous parts from our breadboard, leaving only the 74HC595 shift register, 8-segment LED bar graph display, and any associated resistors and wires. We will use Arduino pins 11, 12, and 13 to drive the shift register's **SER**, **RCLK** and **SRCLK** inputs, respectively. You should aim to achieve a layout that resembles the one illustrated in Fig.2.

Observe that the 10kΩ pull-down resistor connecting the shift register's active-low **$\overline{\text{OE}}$** to the 0V rail stays as-is. This is because, for our purposes, we always want this pin to be in its active state, thereby ensuring that the shift register's outputs are always enabled.

Also observe that since we are no longer controlling the shift register's active-low **$\overline{\text{SRCLR}}$** input with the Arduino, we've added a 10kΩ pull-up resistor connecting this pin to the +5V rail, placing it in its inactive state.

You can see a full breadboard layout in the file named **CB-nov25-brd-01.pdf**. As usual, all files mentioned in this column are available as part of the November 2025 download package from the PE website at **https://pemag.au/link/ac8h**

Make it count!

How about we create a quick program that loops around counting from 0 to 255 (that's 00000000 to 11111111 in binary or 00 to FF in hexadecimal), displaying each value on our 8-segment display and pausing for one second between values? "That's a great idea", I hear you say. You're right, it is, so you go first, and we'll compare our code at the end.

You're ready? Wow, that was fast! You're getting good at this.

This program is short enough that it's probably worth going through in its entirety, not least because it will soon form the basis for driving the displays on our games console. You can download my version in the file named **CB-nov25-code-01.txt**.

As usual, we start with definitions, then declare and assign pins

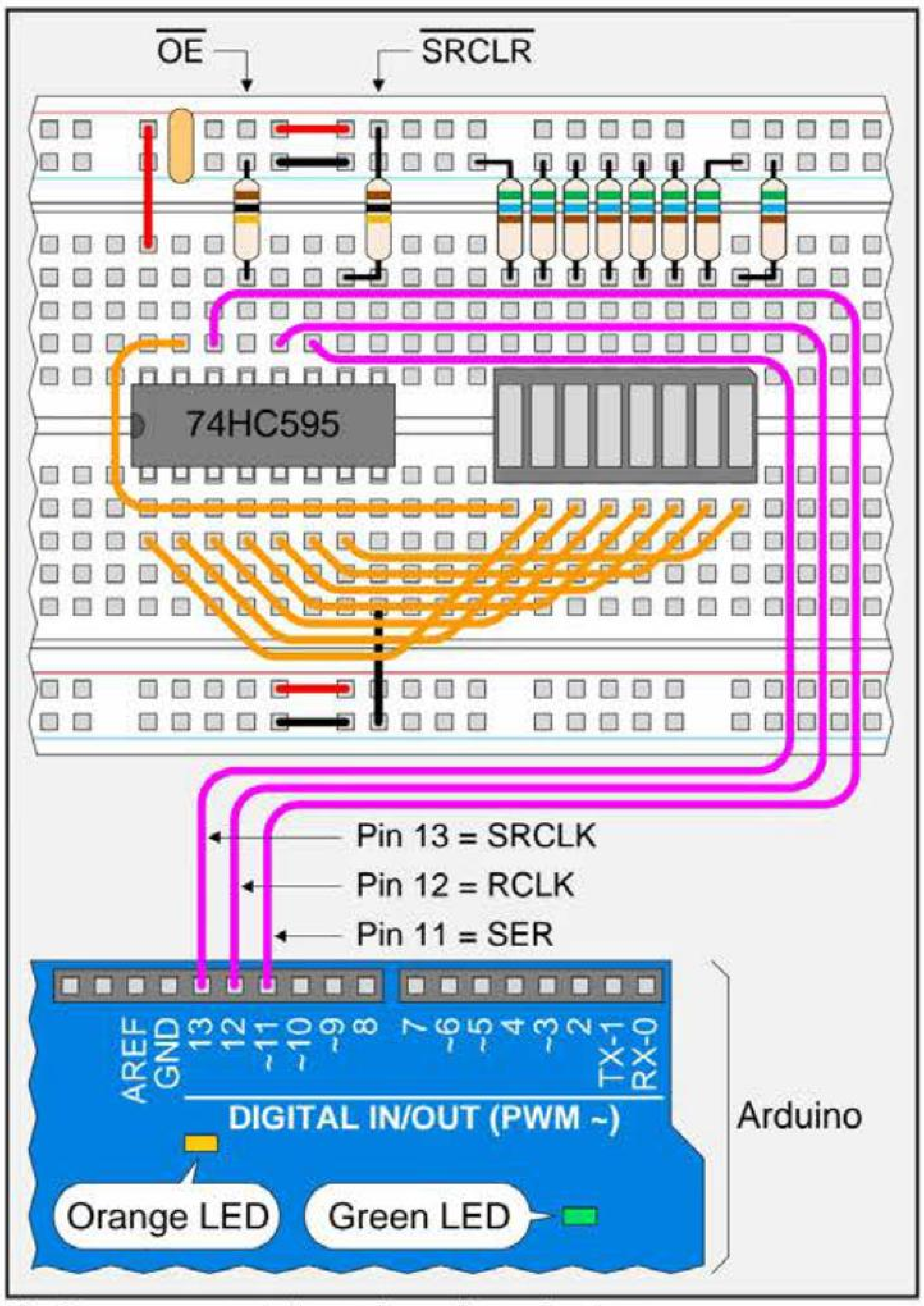

Fig.2: our new cut-down breadboard setup.

```
1   // Display binary count on SR
2
3   // Display Stuff
4   #define NUM_SEGS                8
5
6   // Shift Register (SR) Stuff
7   #define SR_INACTIVE           LOW
8   #define SR_ACTIVE            HIGH
9
10  // Extras
11  #define UPDATE_RATE          1000
12
13  // Declare pins driving the SR
14  const int PinSER   = 11;
15  const int PinRCLK  = 12;
16  const int PinSRCLK = 13;
17
18  // Declare global variables
19  uint8_t CountVal = 1;
```

Listing 1(a): definitions and declarations.

and global variables, as shown in Listing 1(a). Remember that we are using the convention that the listing number (1 in this case) corresponds to the numerical part of the matching code file name ("01" here).

On line 4, we define **NUM_SEGS** (the number of segments in our bar graph display) to be 8. We've seen this before. The only reason I mention it here is that this will also work with (apply to) our 7-segment displays in the future. Recall that these have seven main segments along with an extra decimal point segment.

Since all the shift register's active-low inputs are now hard-wired to their appropriate logic values, I've decided to simplify things by defining common active and inactive states on lines 7 and 8. I've also defined the update (refresh) rate as being 1000ms (one second) on line 11.

On lines 14, 15, and 16, we declare the names of the variables we're going to use to drive the shift register's **SER**, **RCLK** and **SRCLK** inputs, and assign them pin numbers 11, 12 and 13, respectively. On line 19, we declare an 8-bit unsigned integer called **CountVal** and assign it an initial value of 1 (we introduced fixed-width data types like **uint8_t** in the May 2025 column).

Earlier, we stated that our counter will loop around, counting from 0 to 255, and it will certainly do so on subsequent iterations. We've initialised **CountVal** with a value of 1, meaning we will count from 1 to 255 on the first iteration, because this will facilitate comparisons between the actions of this program and those of our follow-up experiment.

Now let's consider the three utility functions shown in Listing 1(b). We'll commence with the **ClearSR** (clear shift register) function, which starts on line 48. This accepts an 8-bit unsigned integer parameter called **numBits**, which contains the number of bits in the shift register.

```
47  // Clear the shift register
48  void ClearSR (uint8_t numBits)
49  {
50    // Set serial data to 0
51    digitalWrite(PinSER, SR_INACTIVE);
52
53    for (int iBit = 0; iBit < numBits; iBit++)
54    {
55      digitalWrite(PinSRCLK, SR_ACTIVE);
56      digitalWrite(PinSRCLK, SR_INACTIVE);
57    }
58  }
59
60  // Load 8-bit value into the shift register
61  void LoadSR (uint8_t thisByte)
62  {
63    for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
64    {
65      digitalWrite(PinSER, (thisByte & 1));
66      digitalWrite(PinSRCLK, SR_ACTIVE);
67      digitalWrite(PinSRCLK, SR_INACTIVE);
68      thisByte >>= 1;
69    }
70  }
71
72  // Copy shift register into output register
73  void LoadOR ()
74  {
75    // Load the output register
76    digitalWrite(PinRCLK, SR_ACTIVE);
77    digitalWrite(PinRCLK, SR_INACTIVE);
78  }
```

Listing 1(b): some utility functions for manipulating the shift register IC.

Since we are currently using a single '595 integrated circuit (IC or 'chip') to implement our shift register, we know that it contains only eight bits. The reason for specifying the number of bits as a parameter is to future-proof this portion of our code, allowing it to support a chain of multiple cascaded '595 chips without modification.

On line 51, we set the shift register's **SER** input to 0. On lines 53 to 57, we apply the required number of positive-going pulses to the shift register's **SRCLK** input to load all its bits with 0s.

Now let's turn our attention to the **LoadSR()** (load shift register) function, which starts on line 61. This accepts an 8-bit unsigned integer called **thisByte**, containing the value we wish to display. On line 63, we declare a **for()** loop that will execute eight times (because 8 is the value we've assigned to **NUM_SEGS**).

Each time around this loop, we perform four tasks. On line 65, we use the **&** (AND) operator to mask out the least-significant bit (LSB) of **thisByte**. You can think of this as **(thisByte & 0b00000001)**. The result, 0 or 1, corresponds to the value in the LSB. This is written to the shift register's **SER** input.

On lines 66 and 67, we apply a positive-going pulse to the shift register's **SRCLK** input, shifting the value on the **SER** input into the register. Then, on line 68, we shift the value stored in **thisByte** one bit to the right, discarding the LSB we just used and bringing the next bit into the LSB position, ready for the next pass through the loop.

Consider the **LoadOR()** (load the output register) function that commences on line 73. This simply applies a positive-going pulse to the shift register's **RCLK** input, copying the contents of the shift register into the output register, at which point they become visible to the outside world.

Now that we have all this under our belt, we can turn our attention to the **setup()** and **loop()** functions, illustrated in Listing 1(c).

The workings of both of these functions are reasonably self-explanatory. In the case of the **setup()** function, we begin by initialising the pins driving the shift register. Then we call our **ClearSR()** function on line 34 to clear all the shift register bits to 0, followed by a call to our **LoadOR()** function on line 35 to copy the bits from the shift register into the output register.

At this point, they will appear on our display.

When it comes to the **loop()** function, on line 41, we call our **LoadSR()** function to load the shift register with the current value in **CountVal**. On line 42, we call the **LoadOR()** function to copy this value into the output register, at which point it will appear on our display.

On line 43, we increment (add one to) the value in **CountVal**. Since this is an 8-bit unsigned number, when it reaches 255 (11111111 in binary), the next increment will cause it to 'roll over' and contain 0 (00000000 in binary). Finally, on line 44, we pause for a moment to allow us to peruse

```
// Do this one time
void setup ()
{
  // Initialize the SR pins
  pinMode(PinSER,   OUTPUT);
  pinMode(PinRCLK,  OUTPUT);
  pinMode(PinSRCLK, OUTPUT);

  digitalWrite(PinSER,   SR_INACTIVE);
  digitalWrite(PinRCLK,  SR_INACTIVE);
  digitalWrite(PinSRCLK, SR_INACTIVE);

  // Clear the shift register
  ClearSR(NUM_SEGS);
  LoadOR();
}

// Do this over and over again
void loop ()
{
  LoadSR(CountVal);
  LoadOR();
  CountVal += 1;
  delay(UPDATE_RATE);
}
```

Listing 1(c): the **setup()** and **loop()** functions of our test sketch.

```
// Do this over and over again
void loop ()
{
 uint8_t tmpVal = 0b00000001;

  for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
  {
    LoadSR(tmpVal);
    LoadOR();
    delay(UPDATE_RATE);
    tmpVal <<= 1;
  }
}
```

Listing 2(a): implementing a sliding 1 display scheme.

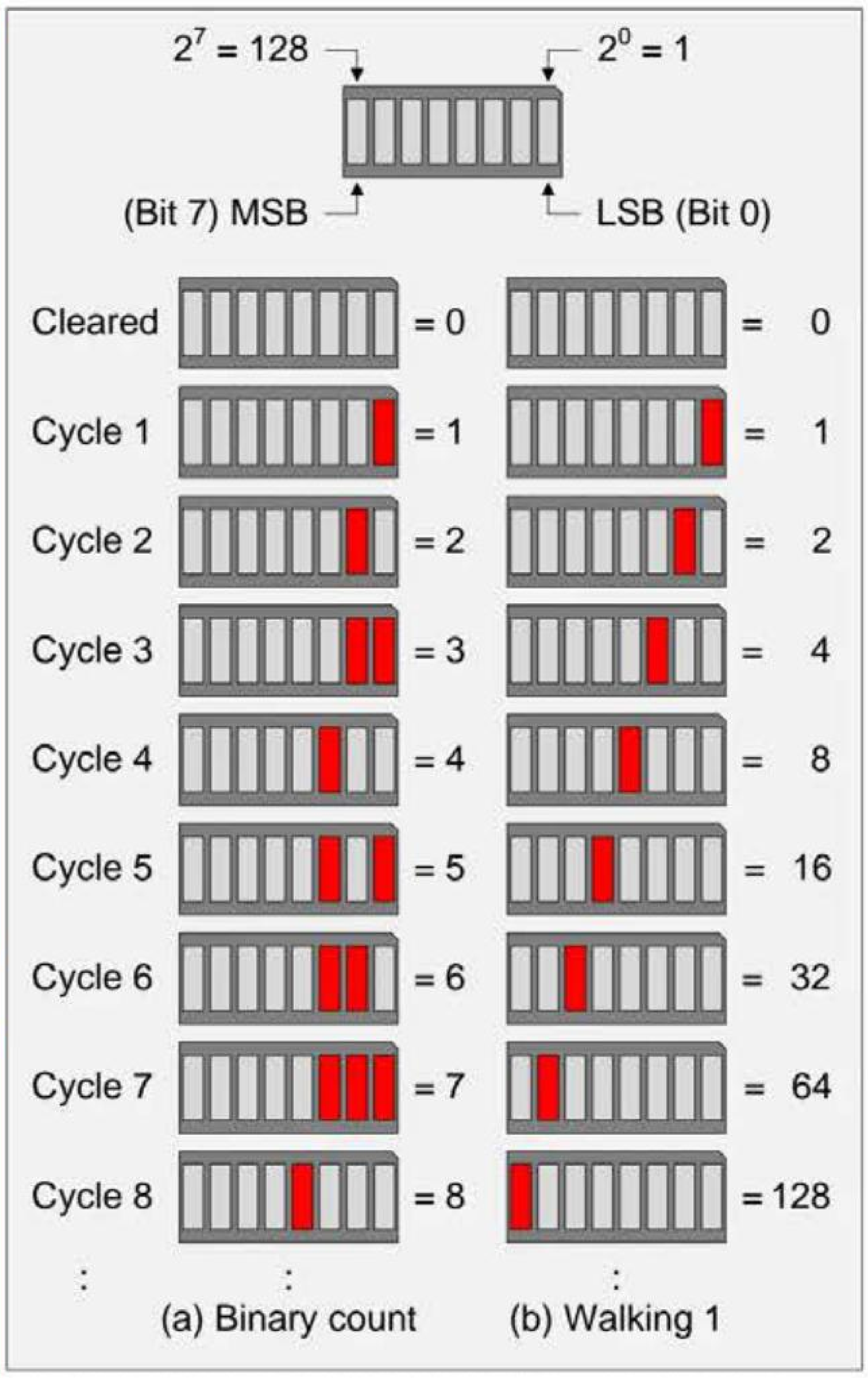

Fig.3: the bargraph display with two test sketches.

and ponder the segments on the display before proceeding to process the next count value.

It's important to wrap our brains around what we are doing here, which is to first load all eight bits into the shift register, and only then copy the contents of the shift register into the output register.

If we loaded the output register every time a new bit was loaded into the shift register, this would result in 'ghosting' on the 8-segment display. That will be due to brief, unintended flashes where incorrect segments appear momentarily before the full, correct pattern is established.

Run this program and observe the binary count being presented on the 8-segment display as illustrated in Fig.3(a). I don't know about you, but I could happily watch this for hours.

Mental gymnastics

To be honest, wrapping one's brain around the way in which all this works can require some mental gymnastics, so you might want to perform some limbering-up exercises before we proceed into the full intellectual floor routine.

In the case of a general-purpose register or a binary data value, the dominant convention in illustrations and our mental models is to consider the least-significant bit (LSB) to be on the right and the most-significant bit (MSB) to be on the left. This is how we think about our **CountVal** variable, as illustrated in Fig.4(a), and our 8-segment display, as shown in Fig.4(c).

Unfortunately, things become a little fuzzier in the case of shift registers like the 74HC595. This is one of those areas where context and convention can collide.

In shift register datasheets, manufacturers typically avoid explicitly using the terms LSB or MSB, as these depend on the user's shifting convention and wiring arrangement. The data sheets just show Q_A to Q_H and the movement of data.

This means that whether Q_A is treated as the LSB and Q_H is treated as the MSB, or vice versa, depends on how we choose to shift the data in (LSB-first or MSB-first), and how we decide to employ the outputs.

In our case, the **LoadSR()** function shifts the **CountVal** value into the shift register starting with the LSB first. This means the LSB of **CountVal** ends up on output Q_H, and the MSB of **CountVal** ends up on output Q_A. Since we've connected Q_H and Q_A to our display's LSB and MSB, respectively, everything works as we want it to (hurrah!).

Slip-sliding along

For reasons that will become apparent shortly, we are going to modify our program to display what we might think of as a "Walking 1" (or a "Sliding 1") pattern, as illustrated in Fig.3(b).

This is easy-peasy lemon squeezy; you can access the new version of this program in the file named **CB-nov25-code-02.txt**. We no longer need our global **CountVal** variable, so we can remove it. Everything else remains the same, except for our **loop()** function, which has been updated to the new version shown in Listing 2(a).

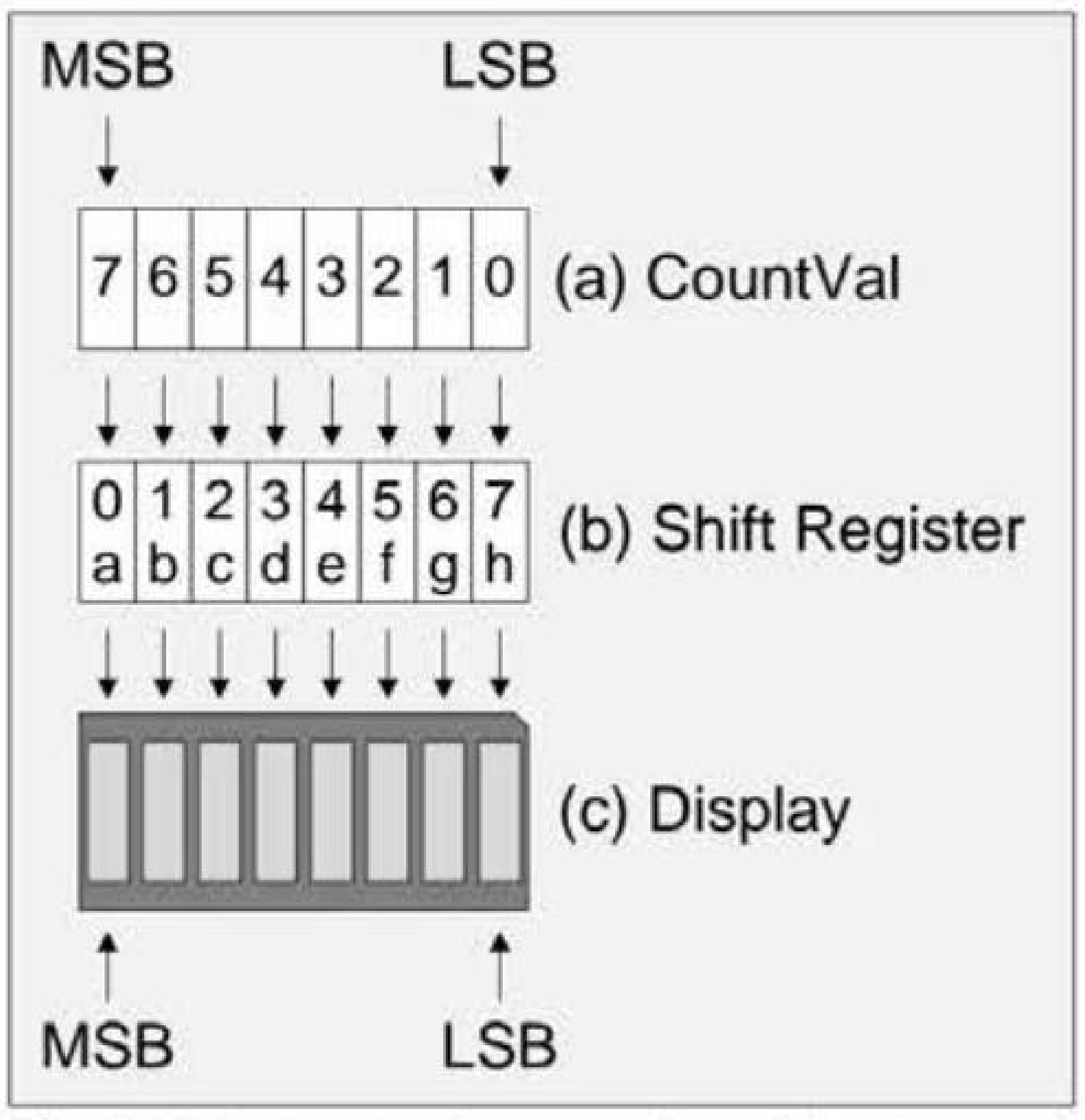

Fig.4. this can make your head hurt.

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We start on line 38 by declaring an 8-bit unsigned integer called **tmpVal** and loading it with binary 00000001. We could have simply said **tmpVal = 1**, but the binary representation helps us better visualise what's going on.

On line 44, we declare a **for()** loop that will execute eight times (because 8 is the value we've assigned to **NUM_SEGS**).

Each time around the loop, we perform four tasks. On line 42, we call our **LoadSR()** function to load the current value in **tmpVal** into our shift register. On line 43, we call the **LoadOR()** to copy the bits from the shift register into the output register, at which point they will appear on our display.

On line 44, we pause to ponder the segments on the display. Finally, on line 45, we shift the contents of **tmpVal** one bit to the left. This will automatically shift a 0 into the LSB, while the MSB will conceptually 'fall off the end' and be discarded.

The result is a classic "Walking 1" pattern, in which our 1 travels from right to left on our display. If we ever wanted to reverse direction and have the 1 move from left to right, we could do so by changing the assignment value on line 38 to **0b10000000**, and modifying line 45 to implement a shift right (**tmpVal >>= 1;**).

We could have simply clocked a logic 1 across the display 'by hand', as it were. To do this, we would first place a 1 on the **SER** input, clock it in with **SRCLK**, and load the output register with **RCLK**. Then we would place a 0 on the **SER** input and repeatedly clock **SRCLK** and **RCLK** to walk the 1 across the display.

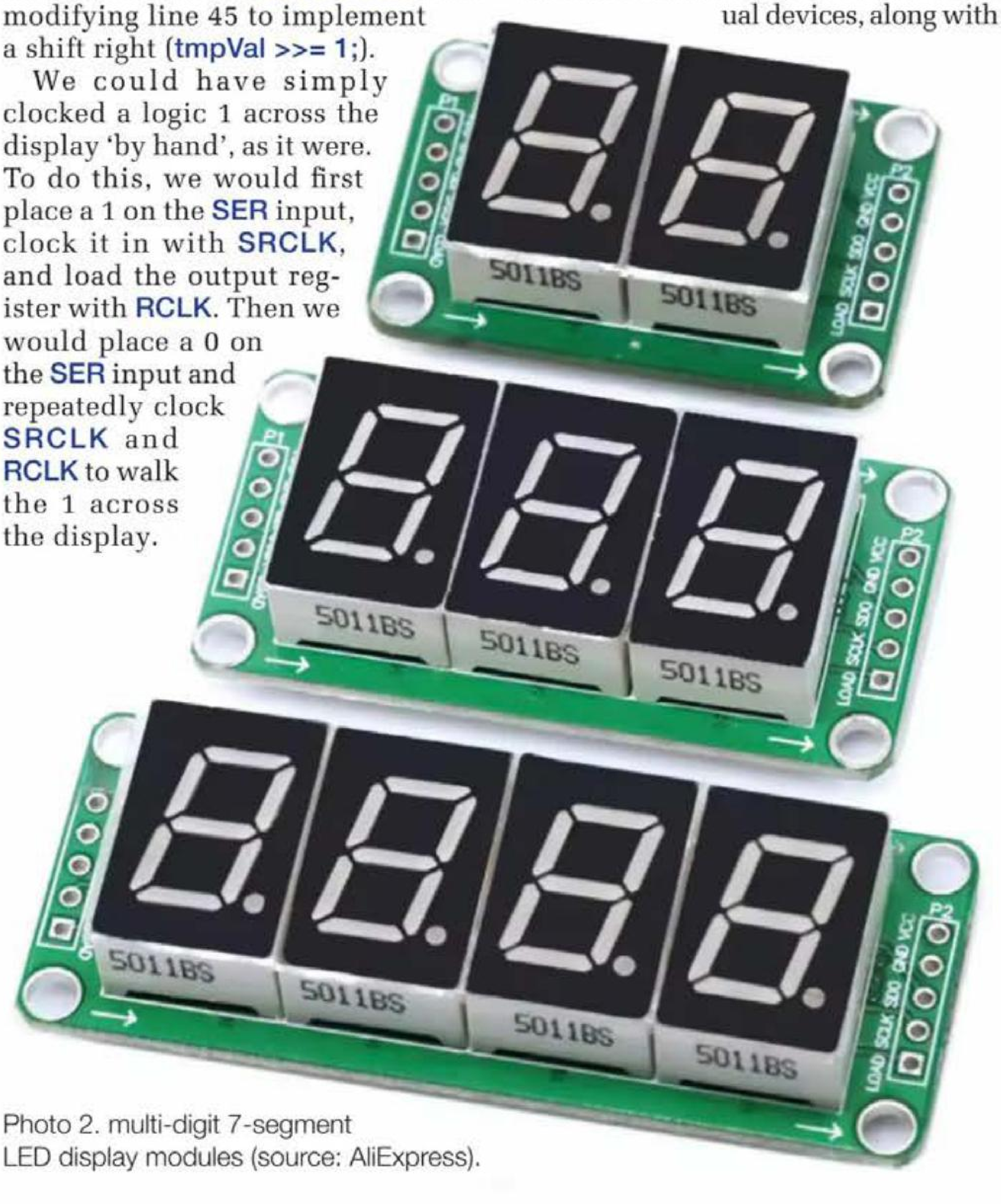


Photo 2. multi-digit 7-segment LED display modules (source: AliExpress).

You could try doing this yourself. For our purposes here, however, I felt it was better to stick with our utility functions because these are what we will be using in the future. After all, the more we use them, the more familiar we become with the way in which they perform their magic.

Run this program and verify that you see the sequence illustrated in Fig.3(b) on your display before proceeding to the exciting part.

Have you got the modules?

I can't help myself. I'm thinking of the old comedy duo Morecambe and Wise (Eric Morecambe looked just like my dear old dad). In particular, the sketches where Ernie Wise would ask a question along the lines of, "Have you got the scrolls?" (or "modules," in our case), and Eric would respond, "No, I always walk this way!" (I'm easily amused).

As we discussed in our January 2025 column, when it comes to the 7-segment displays used on our games console, we could opt to use individual devices, along with associated current-limiting resistors and the 74HC595 shift register chips to drive them. However, it's much easier to work with pre-built modules that already have the components mounted on a small circuit board.

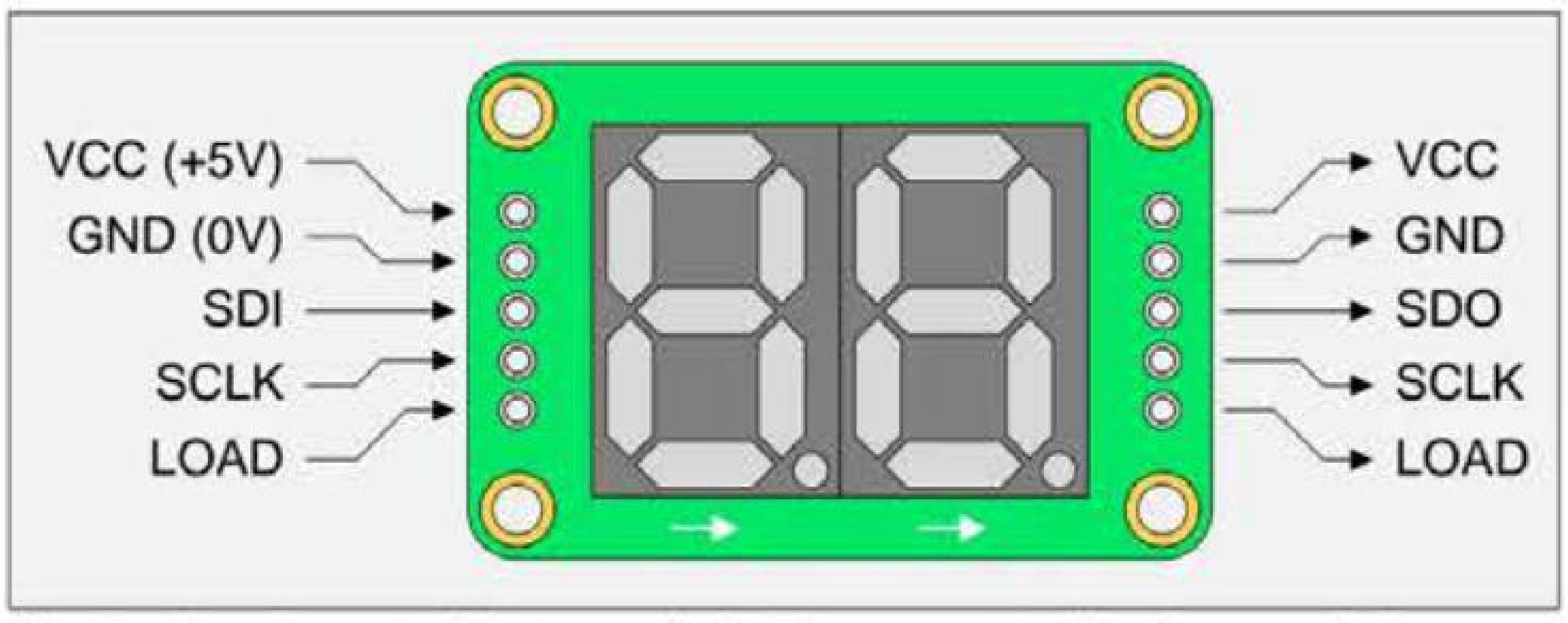


Fig 5: the pinout of a two-digit 7-segment display module.

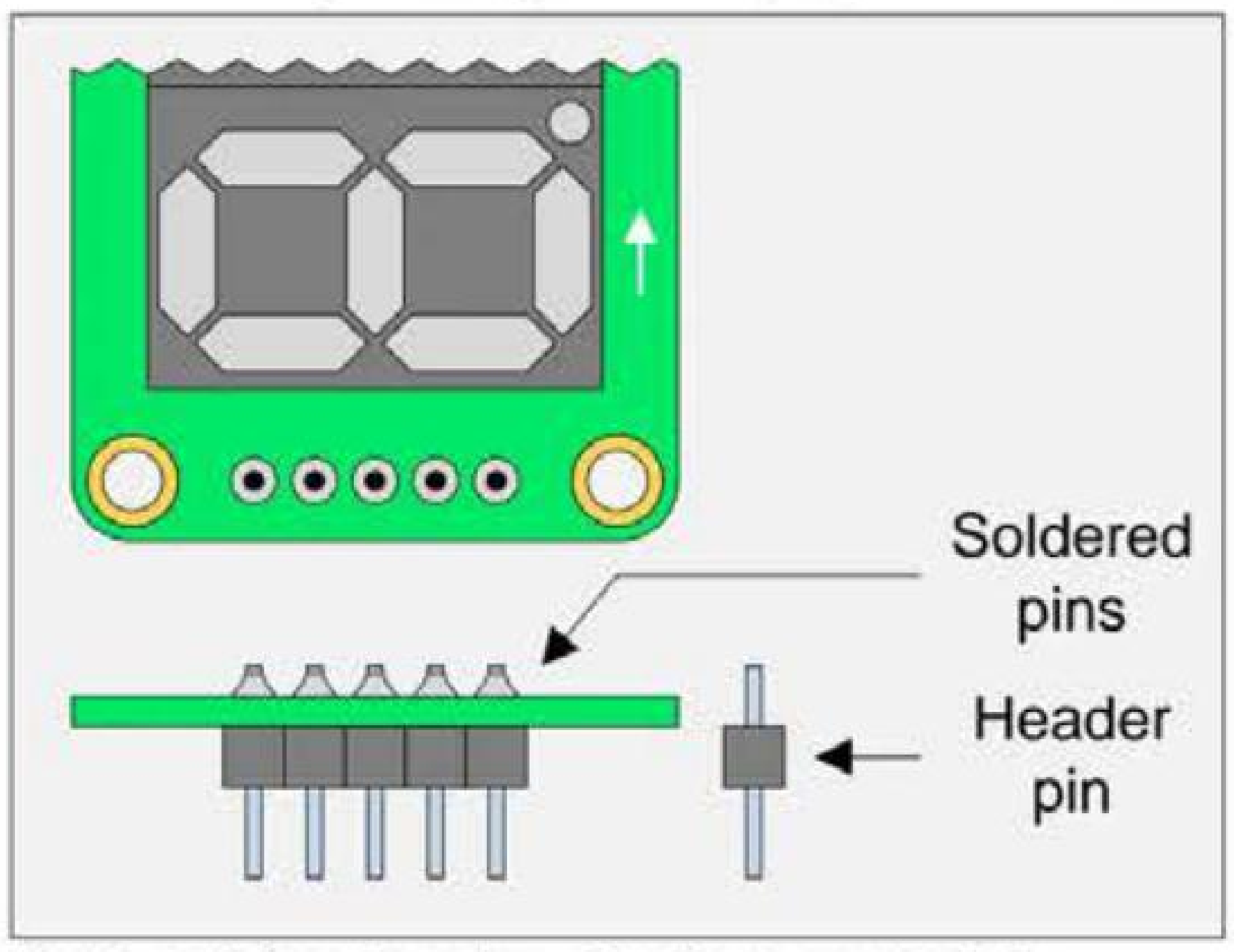


Fig 6: adding header pins to our module.

Modules of this type are available from multiple suppliers, but we would be hard-pressed to beat the prices on AliExpress (https://pemag.au/link/ac8i). These modules are available with two, three or four digits (see Photo 2).

I opted to use three two-digit modules to match the prototype console that was constructed by my friend Joe Farr (shown in Photo 1). However, you can choose to use as few or as many of these two-, three- or four-digit modules as you wish.

A close-up view of one of my two-digit modules is shown in Fig.5. The **SDI** (serial data in), **SCLK** (shift register clock) and **LOAD** signals are equivalent to our existing **SER**, **SRCLK**, and **RCLK** signals, respectively. The **SDO** (serial data out) pin can be used to feed the next module in the chain.

Mounting the components

Just to make sure we know what we're doing (and I use this phrase in the loosest possible sense), we will add five 0.1-inch (2.54mm) pitch header pins (https://pemag.au/link/ac8j) to the input side of one of our modules (the side with the **SDI** input), as illustrated in Fig.6.

Next, we will ensure that everything is powered down and then attach this module to our breadboard, as illustrated in Fig.7. Observe that we've added red and black wires to connect the +5V and 0V pins on the module to the +5V and 0V rails on the breadboard, respectively.

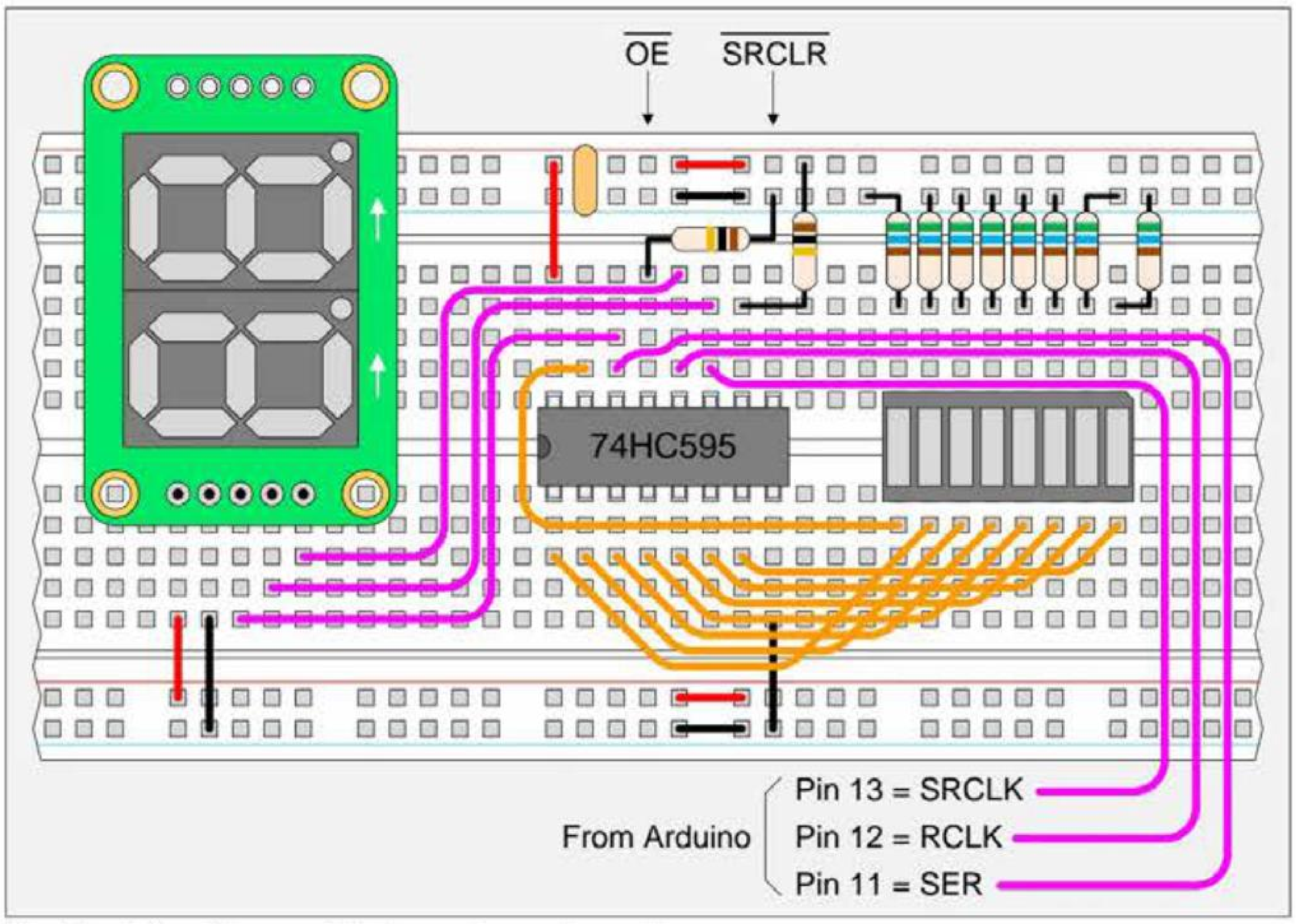


Fig 7: adding the module to our breadboard.

```
3   // Display Stuff
4   #define NUM_SEGS    8 // Segments per display
5   #define NUM_DIGS    2 // Digits (displays)
6   #define ALL_SEGS (NUM_SEGS * NUM_DIGS)
```

Listing 3(a): some additional definitions near the top of our final test sketch.

Additionally, we've added pink wires to extend the **SER**, **SRCLK**, and **RCLK** signals from the '595 chip on our breadboard to also feed the **SDI**, **SCLK** and **LOAD** pins on the module. A full breadboard layout can be found in the file named **CB-nov25-brd-02.pdf**.

The time has come!

We're poised to start driving our 7-segment display module. First, we need to make a minor tweak to our program, shown in Listing 3(a). A full listing is provided in the file named **CB-nov25-code-03.txt**.

As we noted earlier, our original **NUM_SEGS** definition on line 4 remains relevant because it applies both to our old bar graph display and to each of our new 7-segment displays, which include an eighth decimal point (DP) segment.

Our new **NUM_DIGS** definition specifies the number of 7-segment digits we're working with (currently two). This leads us to the **ALL_SEGS** definition, which specifies the total number of segments in our 7-segment display chain. The C/C++ preprocessor will automatically evaluate this to be 8 × 2 = 16.

While the compiler doesn't enforce it, it's imperative to include the **( )** round brackets (parentheses) in this type of macro definition. Otherwise, strange things can happen when we least expect them.

If you look at the program listing, you'll see that we pass **ALL_SEGS** as an argument into the call to the **ClearSR()** function from the **setup()** function.

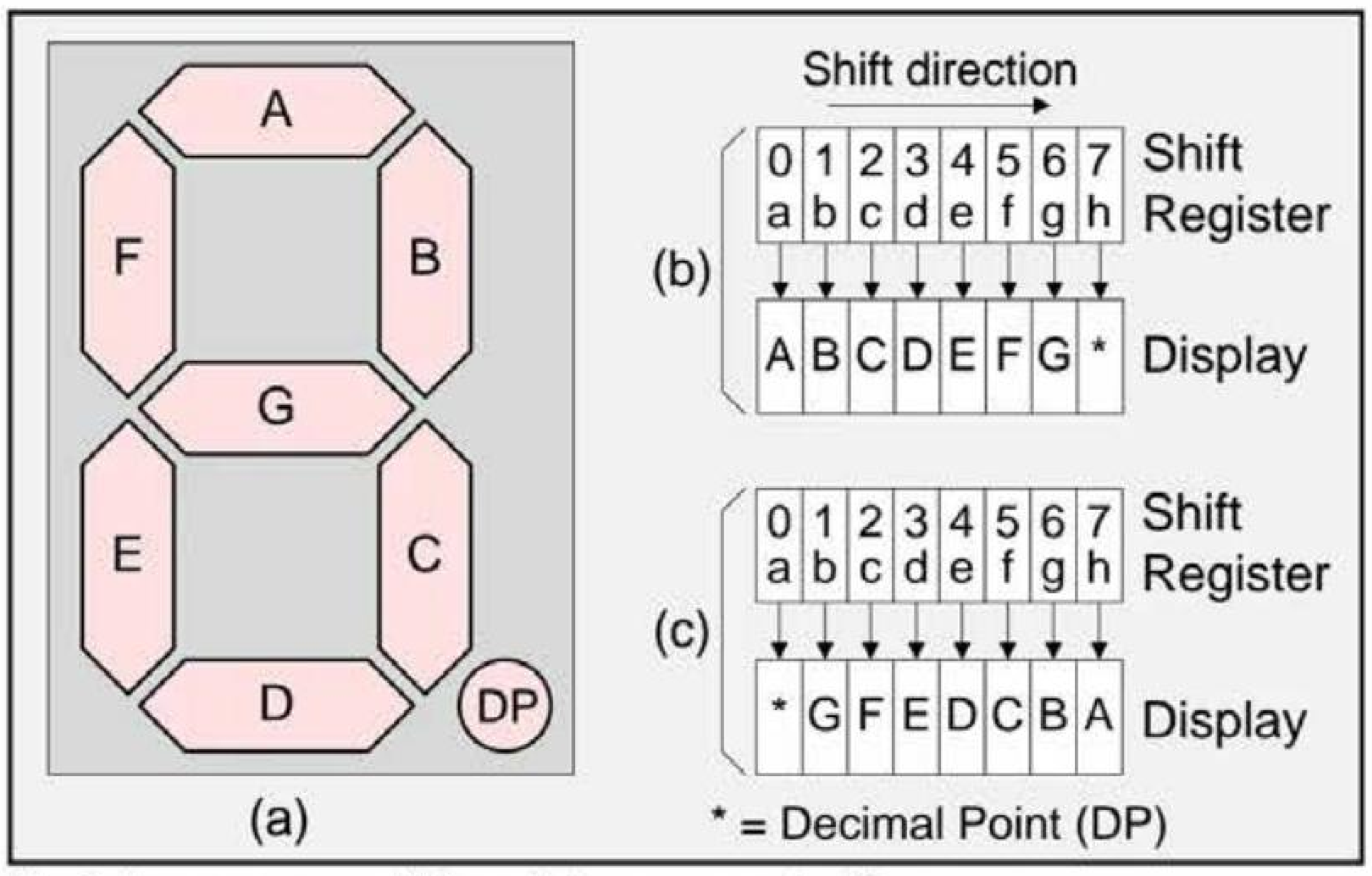


Fig.8: how are our shift registers connected?

Let's pause for a moment to consider what we expect to see before running this new version of our program. I'll give you a clue. We don't know how the makers of our 7-segment display modules decided to connect the display chips to the shift register chips.

From our *Arduino Bootcamp* columns, we know that the segments on the displays are referred to as A, B, C, D, E, F, G and DP, as illustrated in Fig.8(a).

What we don't know in the case of our modules is whether output **a** from the shift register drives segment A on the display, as shown in Fig.8(b). In this case, we would expect to see results as per Fig.9(b). Alternatively, if output **h** from the shift register drives segment A on the display, like in Fig.8(c), we would expect to see results like in Fig.9(c).

This is another example of a situation that requires some mental agility on our part. Remember that we aren't shifting bits individually. The way our program is written, we shift an entire byte into the shift register before loading (copying) it into the output register. Apart from anything else, this explains why the right-hand digit in the display pair lags the left-hand digit by one cycle.

When you're ready, run the program and observe the results.

I didn't see that coming!

I wasn't sure whether to expect the sequence shown in Fig.9(b) or Fig.9(c). You can only imagine my surprise at seeing the sequence depicted in Fig.9(d)!

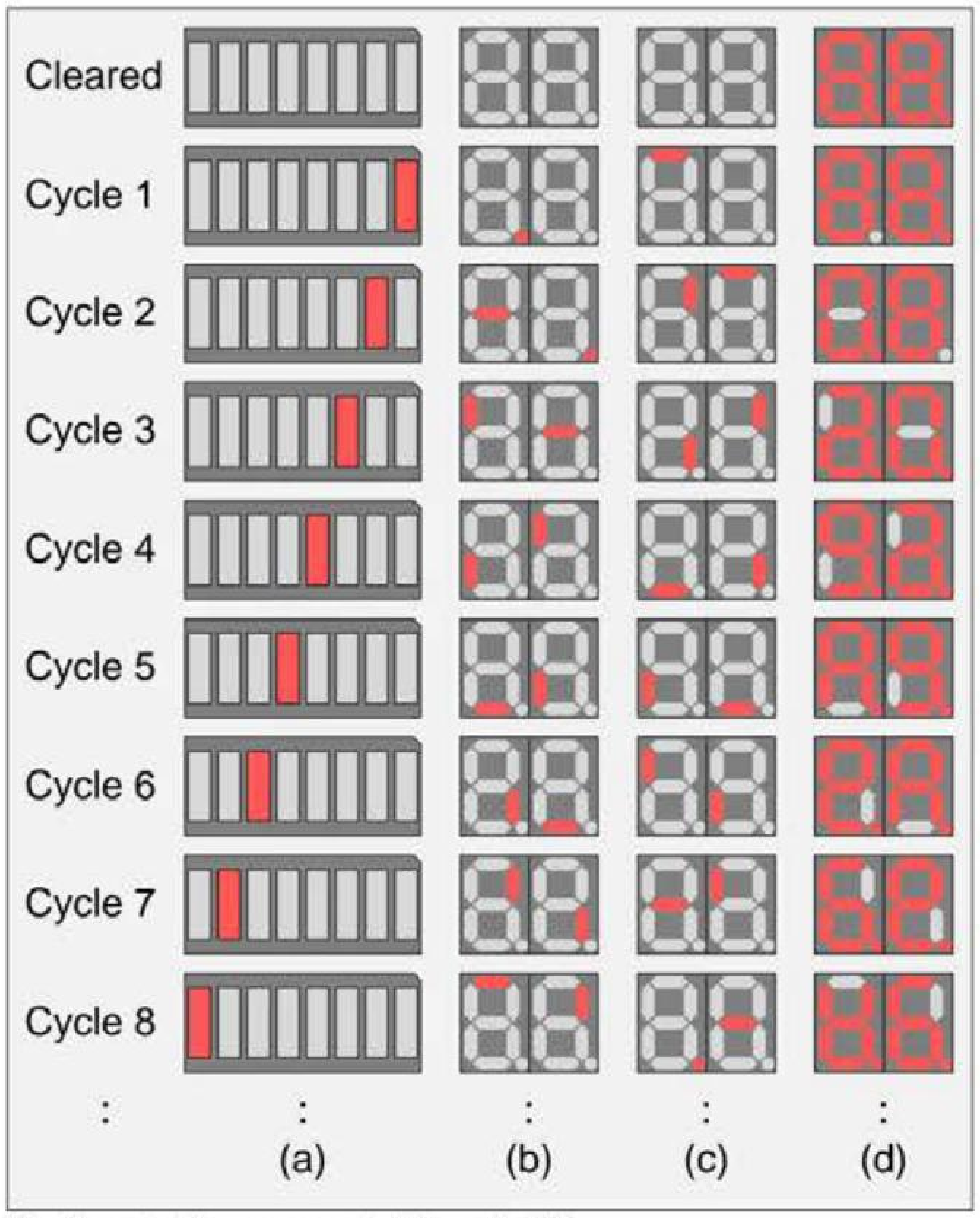


Fig.9: what's connected to what?

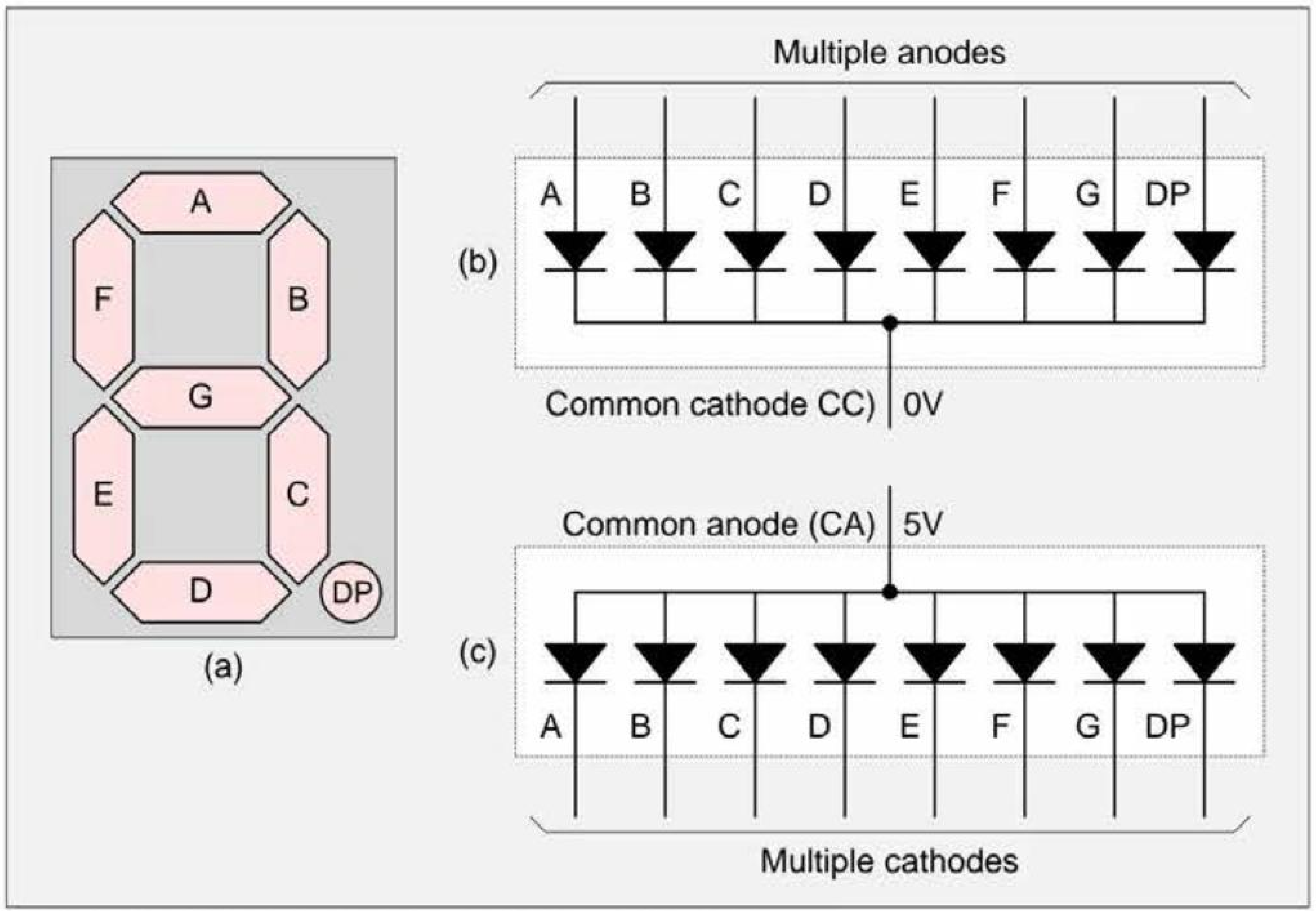
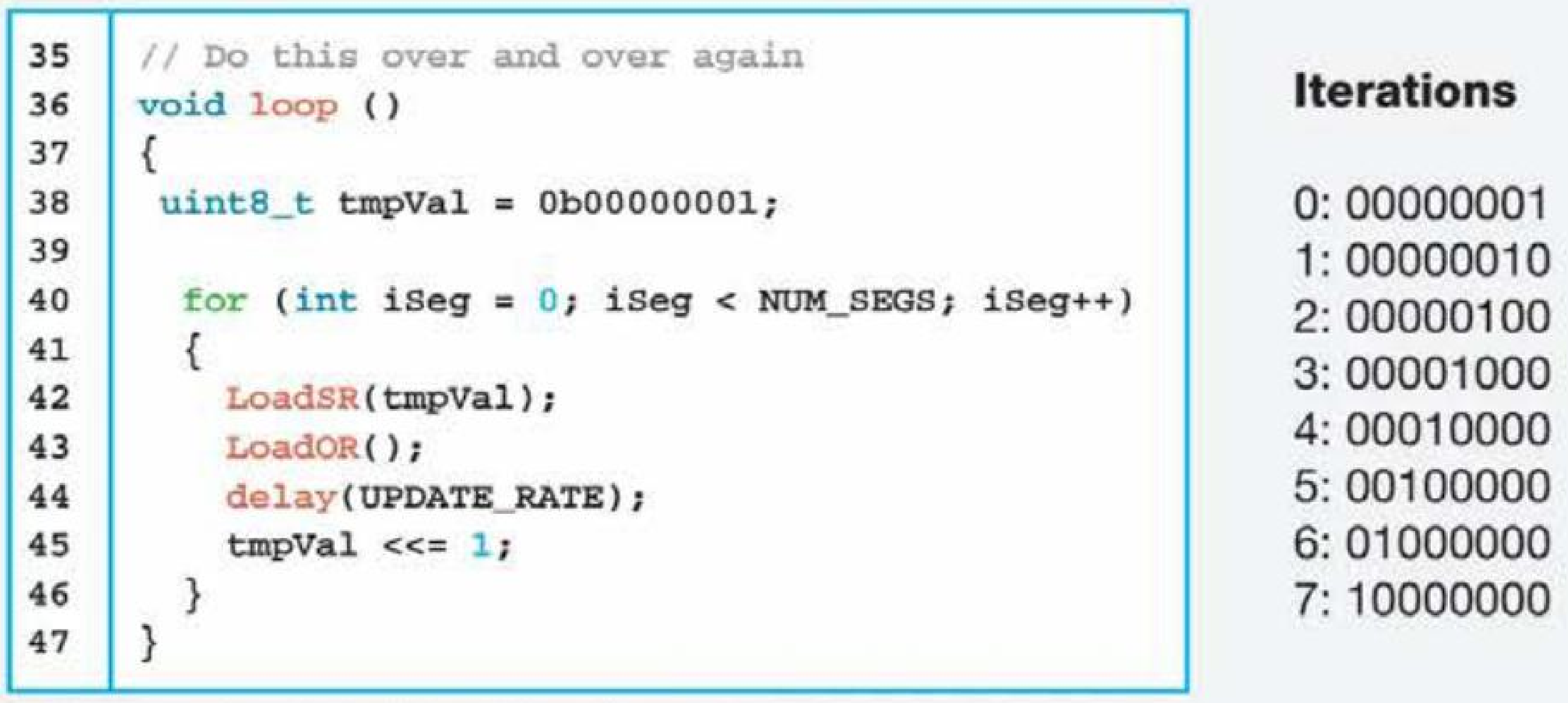


Fig.10: my displays are of the common anode type.

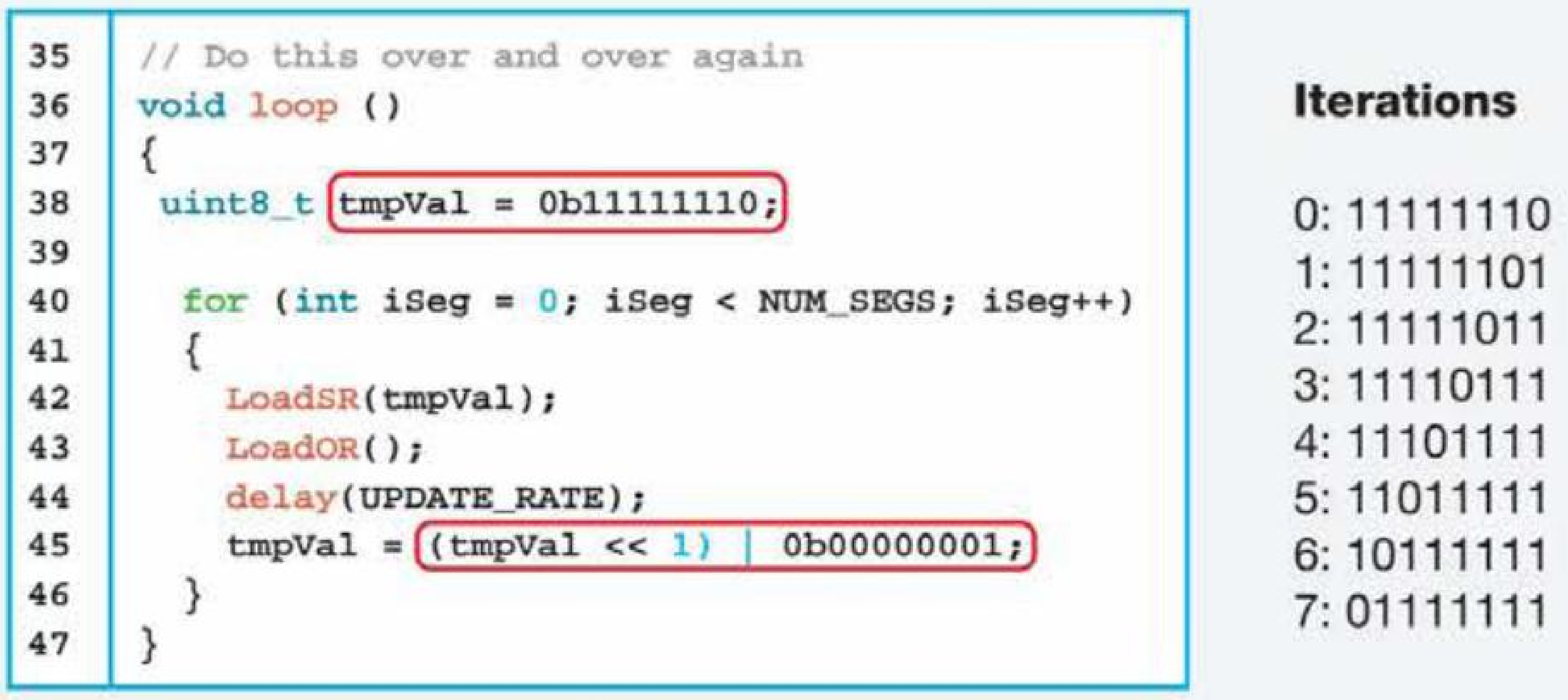


```
35  // Do this over and over again
36  void loop ()
37  {
38   uint8_t tmpVal = 0b00000001;
39
40    for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
41    {
42      LoadSR(tmpVal);
43      LoadOR();
44      delay(UPDATE_RATE);
45      tmpVal <<= 1;
46    }
47  }
```

```
Iterations

0: 00000001
1: 00000010
2: 00000100
3: 00001000
4: 00010000
5: 00100000
6: 01000000
7: 10000000
```

(a) Option 1: original "walking 1" code.

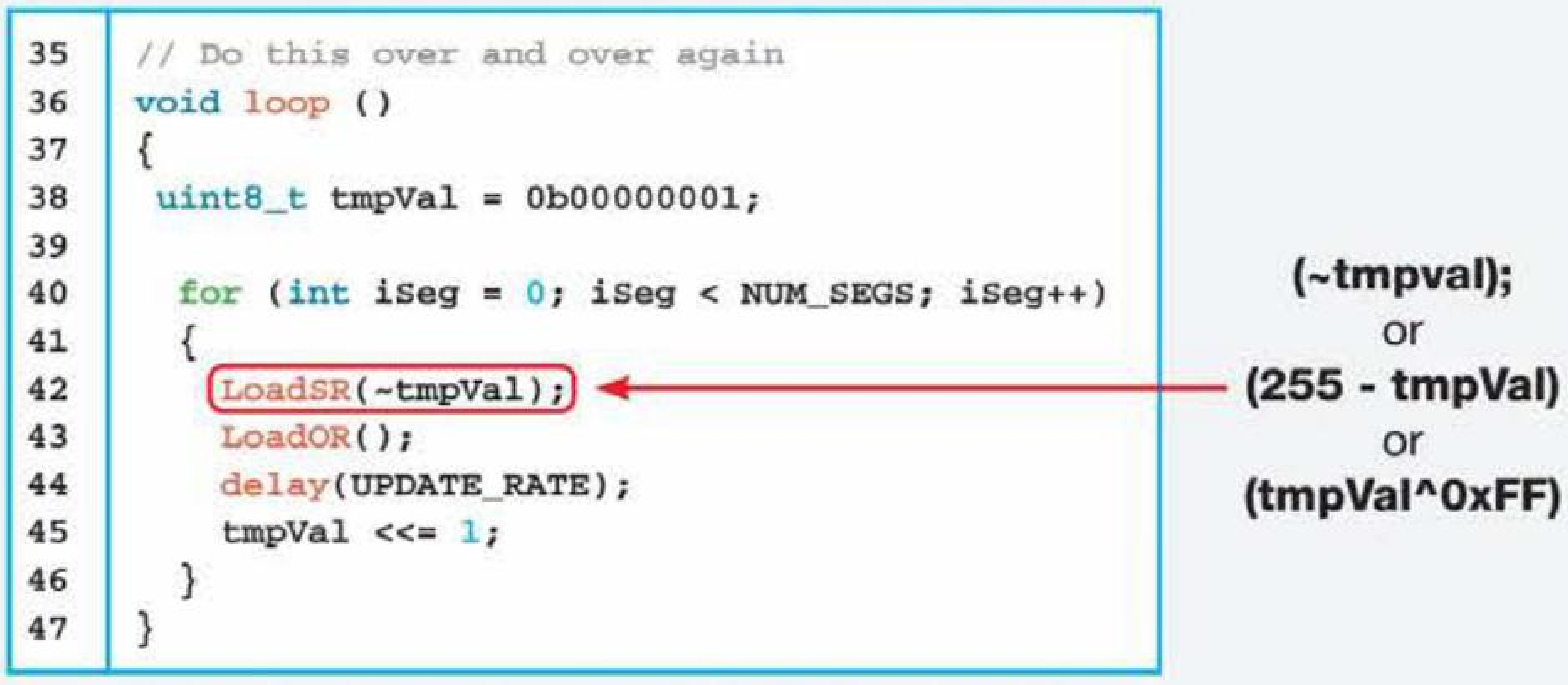


```
35  // Do this over and over again
36  void loop ()
37  {
38   uint8_t tmpVal = 0b11111110;
39
40    for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
41    {
42      LoadSR(tmpVal);
43      LoadOR();
44      delay(UPDATE_RATE);
45      tmpVal = (tmpVal << 1) | 0b00000001;
46    }
47  }
```

```
Iterations

0: 11111110
1: 11111101
2: 11111011
3: 11110111
4: 11101111
5: 11011111
6: 10111111
7: 01111111
```

(b): Option 2: employ a "walking 0" strategy.



```
35  // Do this over and over again
36  void loop ()
37  {
38   uint8_t tmpVal = 0b00000001;
39
40    for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
41    {
42      LoadSR(~tmpVal);
43      LoadOR();
44      delay(UPDATE_RATE);
45      tmpVal <<= 1;
46    }
47  }
```

(~tmpval);
or
(255 - tmpVal)
or
(tmpVal^0xFF)

(c) Option 3: invert the value passed to the **LoadSR()** function.

Fig.11: three different ways to resolve the CA vs CC LED array problem.

This means that the shift registers in my modules are connected to their 7-segment displays as shown in Fig.8(b). However, the displays themselves aren't the common cathode (CC) types we grew to know and love in our *Arduino Bootcamp* columns, like in Fig.10(b). No siree Bob! These displays are of the common anode (CA) persuasion, per Fig.10(c).

In the case of common cathode displays, which I initially thought I was using, a logic 1 (**HIGH**) switches the corresponding segment on, while a logic 0 (**LOW**) turns it off. Things work the other way around with the common anode displays, which I find I'm actually using. In this case, a logic 1 switches the segment off while a logic 0 lights it up.

Spoiled for choice

There are multiple ways that we can resolve the CA vs CC issue. One approach would be to change our "Walking 1", shown in Fig.11(a), into a "Walking 0", as depicted in Fig.11(b). This would involve two tweaks to our code.

The first occurs on line 41, where we change our initial assignment from **0b00000001** to **0b11111110**. The second occurs on line 48, which is where we perform our shift.

The problem here is that the shift operator will automatically cause a 0 to be inserted into the least-significant (right-hand) bit. In this case, however, we wish to insert a 1. To achieve this, we perform the shift, which inserts a 0, and then use the **|** operator to bitwise-OR the shifted value with **0b00000001**, which will force the least significant bit to be 1.

Different people approach these things in various ways. Personally, I dislike the "Walking 0" solution because my own mental model equates 1 with on and 0 with off. For this reason, I prefer to stick with using a "Walking 1" but invert the 8-bit **tmpVal** value just before passing it into our **LoadSR()** function, as illustrated on line 45 in Fig.11(c).

Note that, while this causes an inverted copy of **tmpVal** to be passed into the function, it has no effect on the contents of **tmpVal** itself.

In this case, I'm using the idiomatic **~** bitwise-NOT operator to invert the bit pattern stored in **tmpVal**. It swaps each 0 for 1 and vice versa.

We could achieve the same effect in other ways. For example, we could subtract the value in **tmpVal** from 255 in decimal (**0b11111111** in binary or 0xFF in hexadecimal). For example, 42 = 00101010 in binary, and 255 – 42 = 213, which is 11010101 in binary (I feel a little "tra-la" is called for).

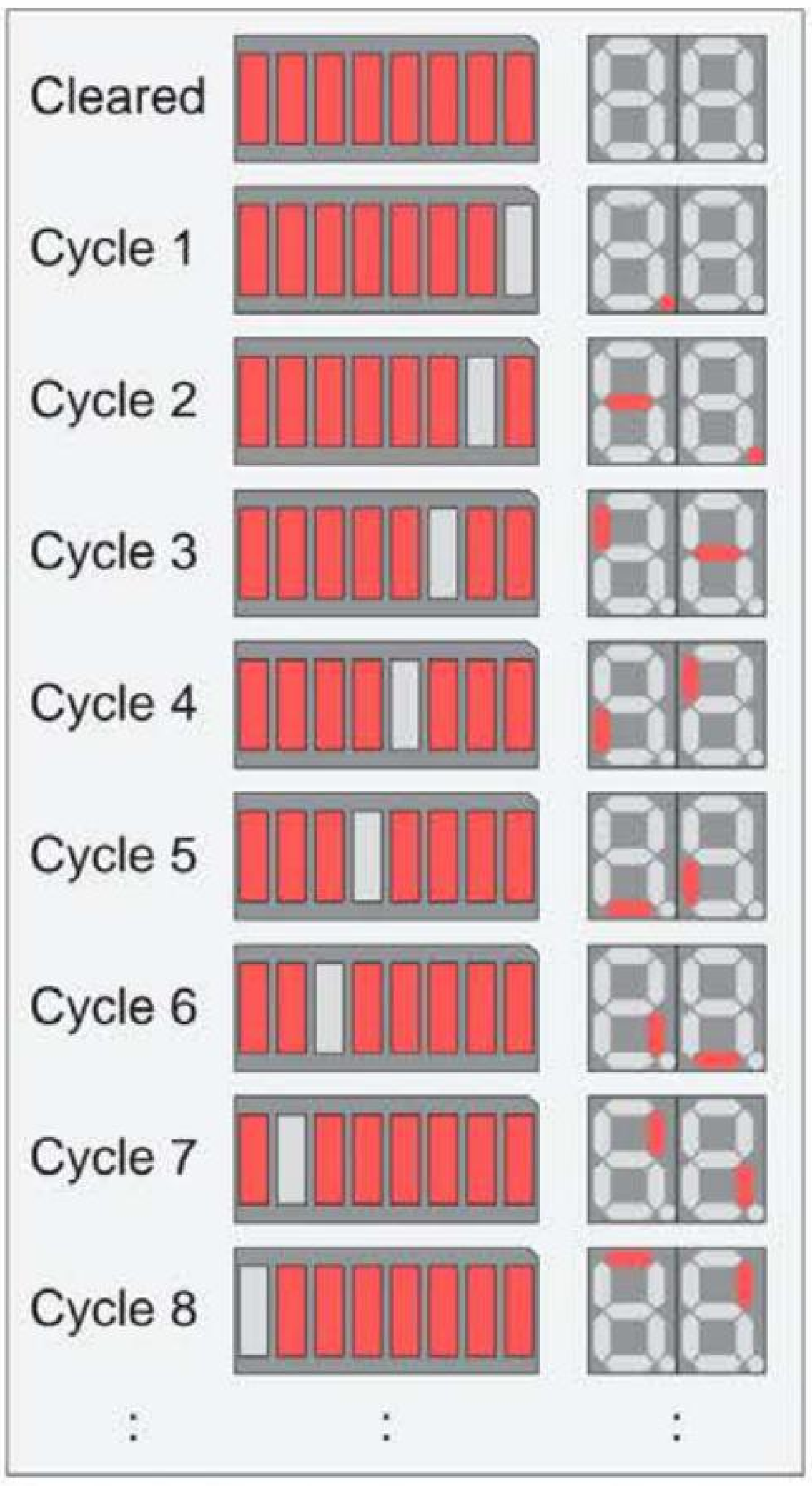


Fig.12: finally, what I was expecting!

Yet another alternative is to use the ^ bitwise-XOR operator, ie, (tmpVal ^ 255) or `(tmpVal ^ 0xFF)` or `(tmpVal ^ 0b11111111)`. This will cause each bit in tmpVal to be XORed with 1, thereby inverting it. You'll see why this works if you look at the XOR truth tables we showed in earlier columns.

I've created an updated version of our program that continues to use a "Walking 1" and inverts the value as it's passed into the LoadSR() function. A full listing is provided in the file named **CB-nov25-code-04.txt**.

When I ran this latest incarnation of my program, I saw the sequence shown in Fig.12. Hooray! Now we're really cooking with a low-density flammable hydrocarbon!

It's necessary to note that, in the case of the cheap-and-cheerful display modules we're using here, any datasheet documentation may be sadly lacking. This means that the modules you purchase could be wired as shown in Fig.8(b) or Fig.8(c). Also, they may turn out to be either CC or CA types, as depicted in Fig.10(b) or Fig.10(c), respectively.

You may not discover the nitty-gritty details until you have these modules in your hot little hands, so you will need to perform your own tests and modify your programs accordingly. We'll talk more about this in our next column, speaking of which…

Next time

In our next column, we will begin displaying real alphanumeric values on our 7-segment displays. Additionally, we will incorporate a full complement of these modules into our games console. There's also a batting chance we'll be adding the eight push-button switches to the console's front panel.

As always, if you have any thoughts you'd care to share on anything you've read here, feel free to drop me an email at max@clivemaxfield.com

Devices and components used in this issue

Arduino Uno R3 microcontroller module	https://pemag.au/link/ac2g
Solderless breadboard	https://amzn.to/3O2L3e8
4-inch (10cm) jumper wires (optional)	https://pemag.au/link/ac2l
8-inch (20cm) jumper wires (male-to-male)	https://amzn.to/3O4hnxk
LEDs (assorted colours)	https://amzn.to/3E7VAQE
Resistors (assorted values)	https://amzn.to/3O4RvBt
Ceramic capacitors (assorted values)	https://pemag.au/link/ac2i
16V 100µF electrolytic capacitors	https://pemag.au/link/ac2j
8-Segment DIP red LED bar displays	https://pemag.au/link/ac2c
74HC595 8-bit shift registers	https://pemag.au/link/ac1n
Dual 7-segment display modules	https://pemag.au/link/ac8i
0.1" pitch header pins	https://pemag.au/link/ac8j

I've no idea
why they
call me
"Max Max"!

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3D Printer Filament Drying Chamber

This device uses relatively simple hardware to keep 3D printer plastic filament warm, driving moisture out and keeping it out. That's important for consistent printing results, especially with PLA or Nylon filament. Your printer can draw the filament directly out of the sealed box.

Part 2 by Phil Prosser

There are two main versions of our Filament Dryer design: one that uses an off-the-shelf plastic box to store the filament, plus a custom timber box made from plywood. While making the timber box isn't all that difficult, it is a bit involved, so we won't go into great detail on how to build it. We think most people will prefer the convenience of simply buying and modifying a pre-made box.

Both solutions perform similarly, although the timber box is, in some ways, a little bit neater. We suggest you read through most of this article before deciding which approach is best for you. Before we get to the boxes, let's build and test the controller electronics.

Controller construction

The controller is built on a PCB coded 28110241 that measures 126 × 93mm. During assembly, refer to its overlay diagram, Fig.3, which shows which parts go where, as well as Photo 4 (note there are some differences between the prototype and final version of the PCB). It is not hard to put together; we have stuck to through-hole parts and easy-to-get bits. The board layout puts all the controls and adjustments along one edge, which we mounted to face the user.

Start by fitting all the resistors. Make sure you use 1% tolerance 12kΩ and 2.7kΩ resistors. The others are not so critical, although we tend to just use all 1% resistors these days as they don't cost that much more than 5% resistors.

Follow by mounting the diodes, ensuring that they are orientated correctly, as shown in Fig.3, and that you don't mix up the four different diode types (again, refer to the overlay). Mount D6 on longer leads so you can bend it to sit in the fan's airflow channel, as shown.

Now install the LEDs. We bent LED7 (red, heater running) and LED12 (green, temperature achieved) over so they are visible from the control side of the PCB once it's installed in the enclosure. LED8 doesn't matter as it's used for its forward voltage, not because it lights up.

Next, fit the 100nF ceramic/MKT capacitors, which are not polarised, then the three electrolytic capacitors, which are. The latter must be inserted with the longer (positive) lead into the pad on the + side. The negative stripe on the can indicates the opposite, negative side.

You can then solder the PIC microcontroller and LM358 operational amplifier. If you bought your PIC from the Silicon Chip store, it will already be programmed. Otherwise, you will need to install CON6 and use a PICkit or similar to program it yourself. The firmware can be downloaded from: siliconchip.au/Shop/6/484

Next, fit the five components in TO-92 packages: four transistors and the LM336BZ voltage reference. Ensure they go in the locations shown and the flat face is orientated as per Fig.3 and the PCB silkscreening. Follow with the headers and trimpots.

While heatsinks are shown for transistors Q1 and Q2, they are not necessary unless you are using a Mosfet with a higher RDS_{ON} than the one we specified (for Q2) or your fan draws more current than the one suggested (for Q1). However, you need to make sure the metal tab side of each device faces to the left, as shown in Fig.3.

Now is also a good time to mount REG1. Like Q1 and Q2, its metal tab must face to the left. Then you can solder the fuse clips in place; it's easier to get them positioned correctly by inserting a fuse before soldering them, but be careful not to overheat it.

On the top side of the board, that just leaves CON1, S1, S2, VR3 and F2, all of which can now be mounted, with the exception of F2.

The thermal fuse warrants some care in soldering, as it will 'blow' at 77°C, which is not hot at all when soldering. We blew the first one we soldered, so be warned!

We dealt with the thermal fuse by using quite long leads and being very fast in soldering. To draw away some of the heat, you could clamp something like pliers (with a rubber band on

3D Printer Filament Dryer, part two

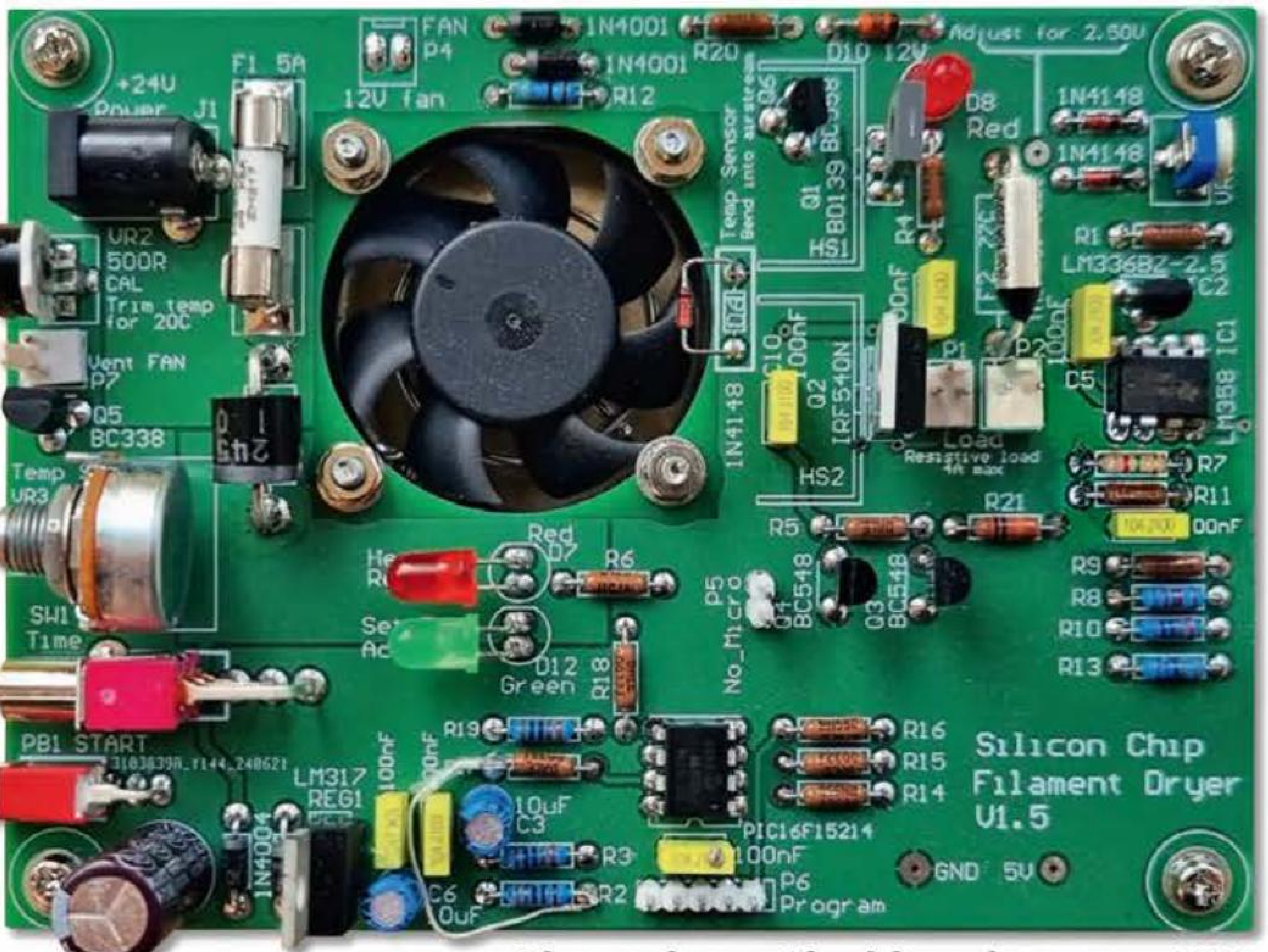

FAN P4
12V fan
1N4001
1N4001
R20
R12
D10 12V
Adjust for 2.50V
+24V Power
J1
F1 5A
VR2 500R CAL Trim temp for 20C
Vent FAN P7
Q5 BC338
Temp VR3
SW1 Time
PB1 START
Temp Sensor Bend into airstream
Q1 BD139
HS1
D8 Red
1N4148
1N4148
R1
LM336BZ-2.5
C2
LM358 IC1
C5
Q2 IRF540N
C10 100nF
1N4148
P1
P2
Load Resistive load 4A max
HS2
R7
R11
R21
R5
R9
R8
R10
R13
Red D7
R6
D12 Green
R18
P5 No_Micro
Q4 BC548
Q3 BC548
R19
R16
R15
R14
Silicon Chip Filament Dryer V1.5
LM317 REG1
1N4004
10uF C3
R3
R2
C6 10uF
PIC16F15214
100nF
P6 Program
GND 5V

Photo 4: the top side of the early prototype PCB, repeated from last month's issue.

the handle), a haemostat (self-closing pliers), or perhaps a clip-on heatsink on the lead between the fuse and pad during soldering.

The fan is installed on the back of the PCB and is intended to push air into the enclosure. If you look at the side of the fan, you will typically see two arrows, one indicating the rotation direction and the other the airflow direction.

If you are using a fan different from the one we got from Altronics, check that yours draws more than 50mA when running and less than 10mA when stalled. This will ensure that the protection system operates as intended. Secure the fan and its 40mm grille on the underside of the PCB using 16mm-long M3 machine screws, hex nuts and shakeproof washers.

You can use a polarised header plug to connect this fan to CON4 or solder its leads directly to the PCB, as it should not usually need to be removed.

At this point, the board should be fully loaded and ready to test. Testing can be done without the heater plates and before the controller is installed in the enclosure.

Testing procedure

Start by applying power and checking for excess heat or smoke. The fan on the PCB should be running all the time; that is normal.

Check that the 5V rail is OK; there are GND and 5V test points in the lower right-hand corner of the PCB. If the voltage between those is not in the range of 4.75-5.25V, check around the LM317 regulator. Are the resistors the correct values? Is there a short on the regulator, PIC or op amp?

Use a DVM to monitor the voltage on the 2.5V test point at upper right and adjust VR1 to get 2.5V on that test point. If you can't do that, check that the LM336-2.5 is the correct part and the right way around.

If the onboard fan is not running, check for about 12V on the "+" pin of CON4, the fan header. If it is present, check that the fan is plugged in the right way around and that the wiring is OK. Also verify that the BD139 transistor (Q1) and 12V zener diode are both the right way around.

Now set the temperature control (VR3) fully anti-clockwise and adjust trimpot VR2 up and down. You should see the green "Set Temp Achieved" light (LED12) switch on and off.

If that does not happen, check the voltage on pin 6 of IC1, the LM358. This is the forward voltage of the temperature sense diode and should be about 0.55V. Also check the voltage on pin 5 of IC1, which is adjusted by VR2. It should vary above and below 0.55V as you rotate VR2.

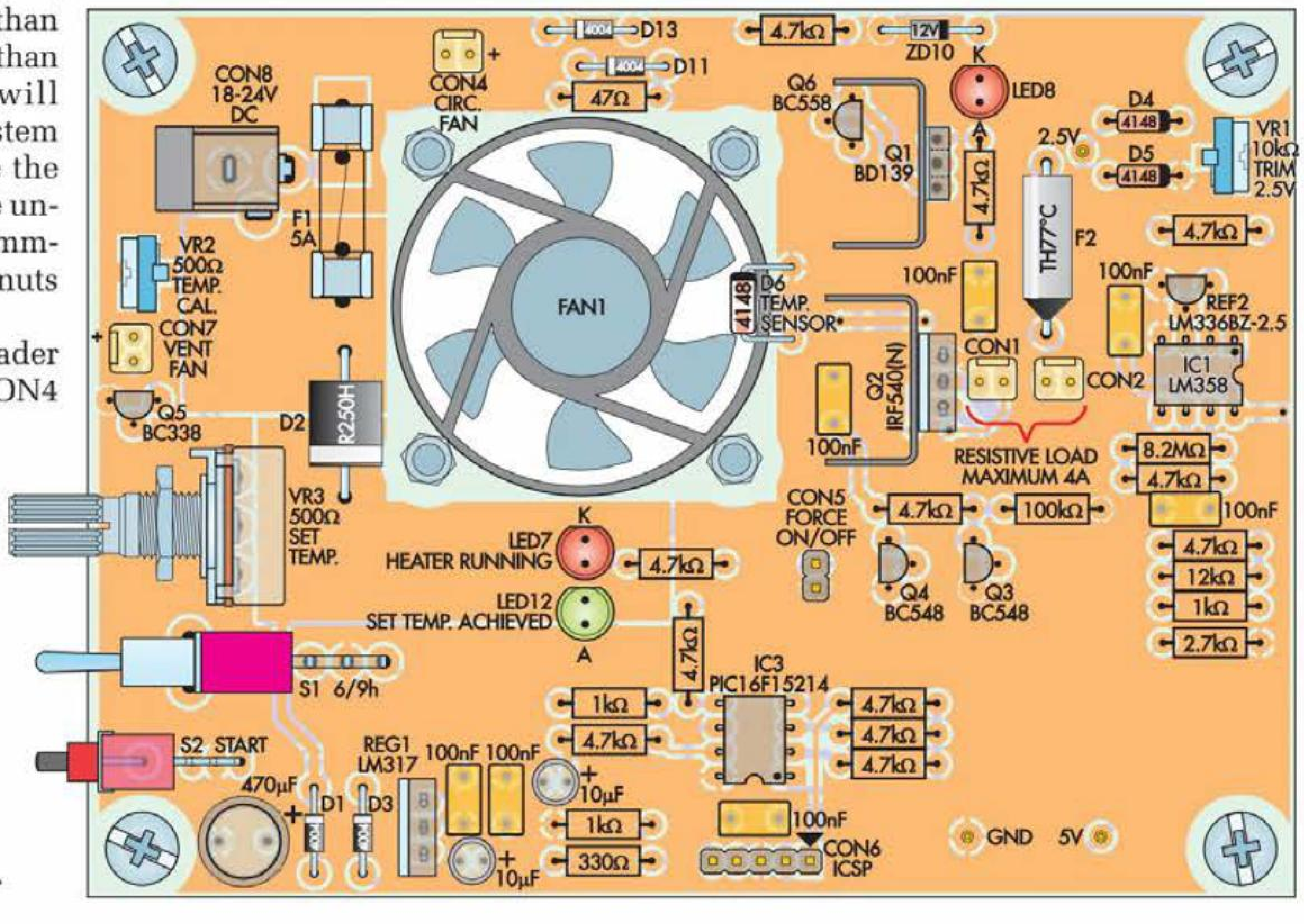

D13
4004
D11
4004
47Ω
4.7kΩ
12V ZD10
K
LED8
A
CON8 18-24V DC
CON4 CIRC. FAN
+
Q6 BC558
Q1 BD139
4.7kΩ
2.5V
D4 4148
D5 4148
VR1 10kΩ TRIM 2.5V
F1 5A
FAN1
D6 4148 TEMP. SENSOR
TH77°C
F2
100nF
100nF
4.7kΩ
REF2 LM336BZ-2.5
VR2 500Ω TEMP. CAL
CON7 VENT FAN
Q5 BC338
D2 R250H
Q2 IRF540(N)
CON1
CON2
IC1 LM358
100nF
RESISTIVE LOAD MAXIMUM 4A
8.2MΩ
4.7kΩ
VR3 500Ω SET TEMP.
CON5 FORCE ON/OFF
4.7kΩ
100kΩ
100nF
LED7 HEATER RUNNING
K
4.7kΩ
Q4 BC548
Q3 BC548
4.7kΩ
12kΩ
1kΩ
2.7kΩ
LED12 SET TEMP. ACHIEVED
A
4.7kΩ
S1 6/9h
IC3 PIC16F15214
1kΩ
4.7kΩ
4.7kΩ
4.7kΩ
4.7kΩ
S2 START
REG1 LM317
100nF
100nF
470μF
D1
D3
10μF
1kΩ
100nF
330Ω
10μF
CON6 ICSP
GND
5V

Fig.3: use this overlay diagram to help you assemble the controller board. All parts mount on the top, except the 40mm fan, which goes on the underside. Its power wires come around to the top side of the board to plug into CON4. Watch the orientations of the ICs, Q1. Mount LED7 & LED12 on long leads bent over to face the left.

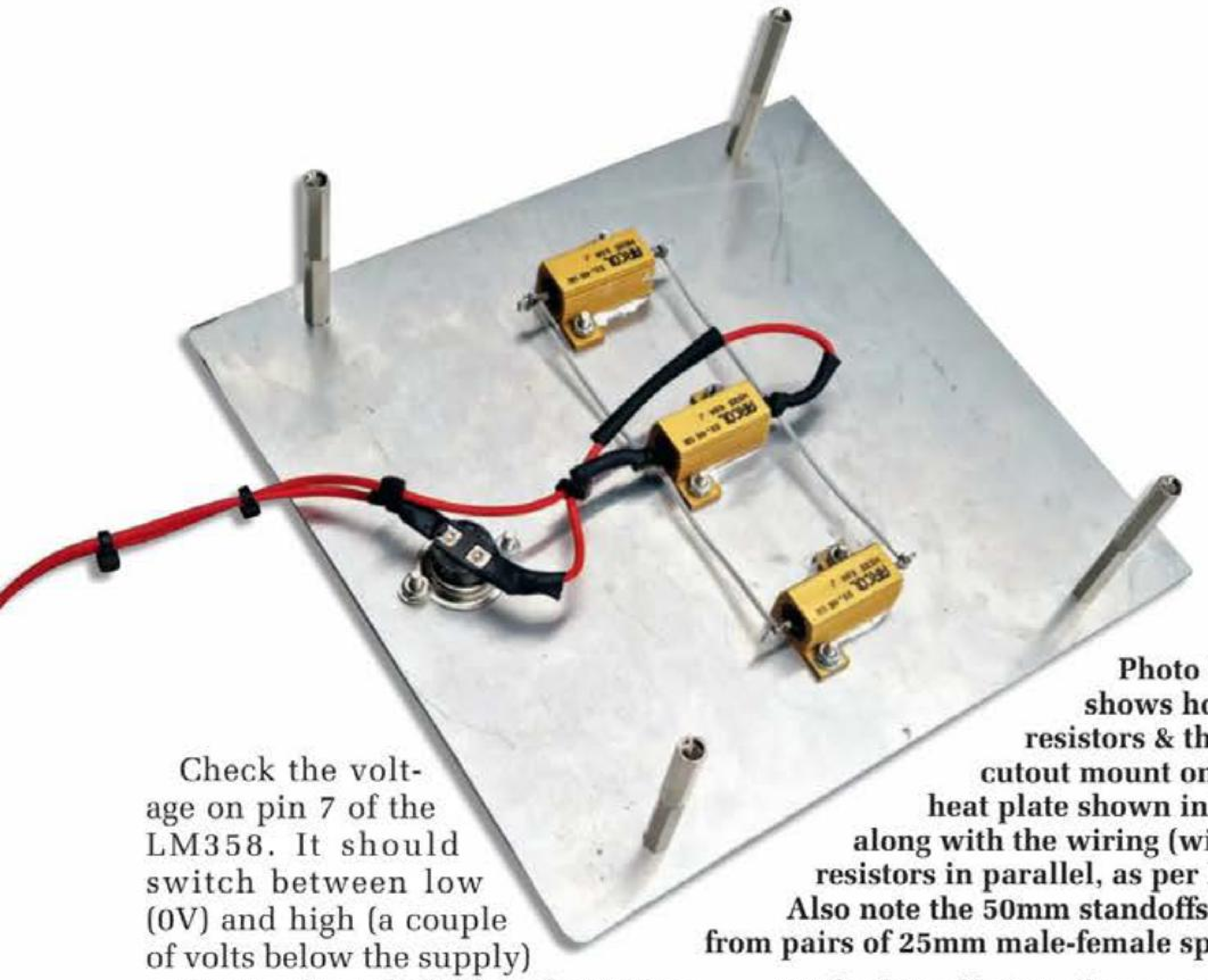


Photo 6: this shows how the resistors & thermal cutout mount onto the heat plate shown in Fig.5, along with the wiring (with the resistors in parallel, as per Fig.4). Also note the 50mm standoffs made from pairs of 25mm male-female spacers.

Check the voltage on pin 7 of the LM358. It should switch between low (0V) and high (a couple of volts below the supply) as VR2 is adjusted. If it does, but LED12 is not lighting, that points to a problem with diode D12, transistor Q3, LED12 or its series resistor.

Now it's time to use VR2 to calibrate the temperature setting. Do this at room temperature (20-25°C). Turn VR3 up a little bit. Yes, that is a technical term; aim for around ⅓ to ¼ of its travel, which corresponds to around 10°C.

Adjust VR2 until green LED12 is off, then slowly rotate it anti-clockwise until LED12 comes on. Once you've done that, VR3 will let you adjust the set point from room temperature to about 30°C above that.

Now if you turn VR3 fully anti-clockwise, LED12 should come on. If it does not, repeat the prior step with the control up a 'little bit more' (another technical term).

Turn VR3 up, and LED12 should go off. Now press the Start button, S2. The red "Heater On" LED, LED12, should light. That means the PIC and Mosfet Q3 are working, as is the thermostat. If not, check that there is about 12V on the left-hand side of the 4.7kΩ resistor between Q3/Q4 and Q2. This is the Mosfet gate drive. If not, verify that you have used a PNP device for Q6.

The PIC output at pin 5 should start high (5V) and go low (near 0V) when you press the Start button, S2. You can check this by monitoring the upper pin of CON5, nearer Q2. If this does not go from high to low when you press S2, check the PIC.

With this all OK, the controller should be working and ready to test and install. The fact that the Mosfet switches the LED indicates it is working.

You are ready to assemble and wire the heater plates, which we will describe in the next section. The approach to use will depend on how you are packaging the Dryer.

Making the heater plates

We are presenting two approaches to the heat plates. These aim to dissipate 50W in the enclosure while keeping surface temperatures to a safe level. With a 50°C enclosure temperature, these plates reach about 70°C. Any aluminium sheet more than 1.2mm thick will work, depending on what you have available.

In deciding how you want to make your heater plates, here are the safety controls you need to consider:

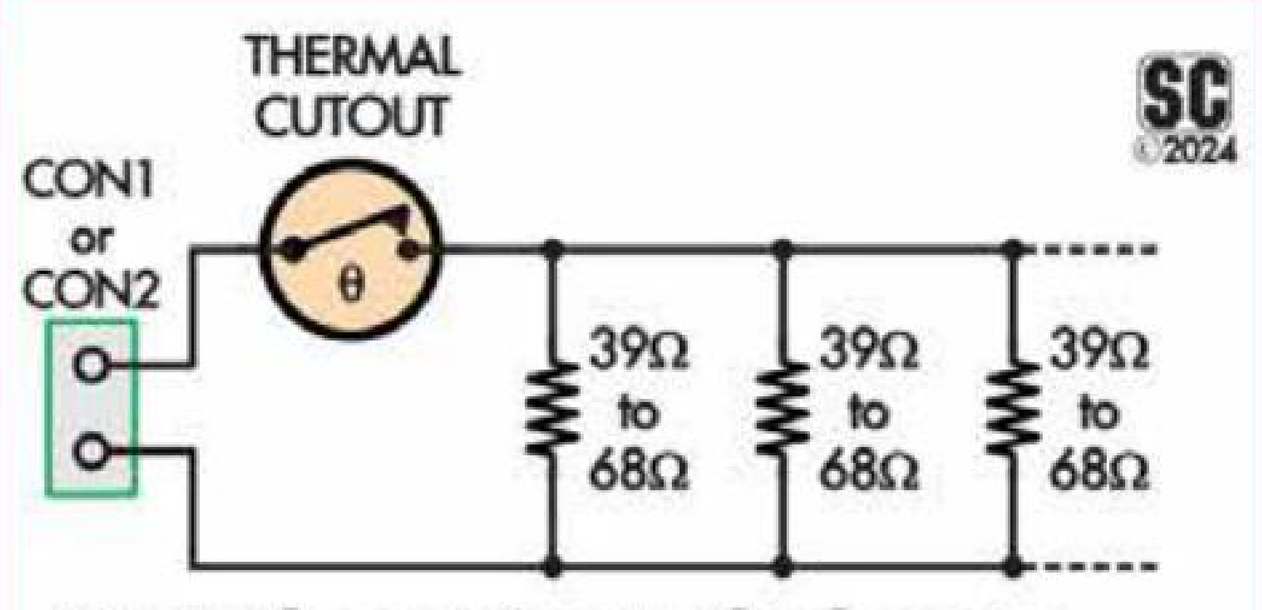


Fig.4: the wiring to the heater resistors is straightforward. If using low-value resistors, you might want to connect them in series rather than parallel. Either way, the thermal cutout must be wired to disconnect all the resistors if it gets too hot.

- Do not place the heat plate in continuous contact with timber; it can auto-ignite. Use standoffs for any heater plate at the bottom of the enclosure.
- Ensure that the circulation fan can circulate air throughout the enclosure.
- Ensure that the air around the temperature sense diode will be representative of the overall enclosure air temperature (good circulation should provide that).
- Ensure that the user can easily access the controls, especially S2.
- Ensure that the 90°C thermal cutout switches are installed and located near the heating resistors.
- Ensure the resistors are securely connected to the plate and will not run excessively hot.

There are two primary considerations for resistor selection. Firstly, they must be able to be affixed to the heatsink securely. Secondly, you must be able to safely dissipate about 50W into your case. Our experiments showed that in a normal room, 50W is adequate to achieve 50°C.

You can use resistors in series or parallel. We had a bunch of 7Ω 25W resistors lying around that we used in one prototype, wired in series. Do your sums and select the resistance you need, then search out the cheapest option. The resistors specified in the parts list (visible in the photos) are pretty close to optimal in terms of ratings, size and cost.

Once you have made the heater plates, it is worth plugging them into the controller on the bench and checking that they work as expected. Once you set the system running, the heater plates should get hot after a few minutes. You should be able to feel that each resistor is dissipating power by touching its case while running; it will be noticeably warmer than the heatsink.

If any resistors are extremely hot, check that they are correctly mounted. If they're all reaching about the same temperature, the heater is ready to go.

Wire up the plate using medium/heavy-duty hookup wire rated to a minimum of 90°C; Altronics carries suitable wire, as stated in the parts list last month. Make the flying leads long enough that you can assemble the box easily. The required connections are shown in Fig.4.

On the controller end of the wires, we recommend crimping them into pluggable header pins and inserting them into the blocks so you can easily plug in and remove the heater boards to the controller. You can use any matching pair of 2.54mm pitch headers and plugs for this, just make sure that the connector is rated for 3A or more (the Altronics ones in the parts list are rated at 3A).

We like to flow a little solder into the crimped joint to ensure it can't come loose, but if you do that, be careful not to add excessive solder or get it on the outside of the pin, or it may no longer fit in the block. The pins often need to be straightened before they will slide into the blocks and click into place. They can be released by pressing the tab with a tiny flat-bladed jeweller's screwdriver.

We recommend against soldering the wires straight to the PCB, as this will make the whole thing very fiddly to handle and assemble.

Making the enclosure

As mentioned previously, you have two options: modify a plastic box or make your own timber box. We won't go into a lot of details for the latter case; we recommend you only take that route if you are confident in sorting out the details yourself.

For the simpler plastic enclosure, the secondary heat plate is just three resistors and a 90°C thermal cutout switch mounted to a 180 × 210mm sheet of 1.5mm-thick aluminium, as shown in Photo 6.

The recommended drilling pattern and mounting locations are in Fig.5. We used 50mm metal threaded standoffs (two 25mm male/female spacers joined) to fix this to the end of our plastic box.

The controller mounts on the primary heat plate, shown in Fig.6 and Photo 7. This uses the same size sheet, but holds the heating resistors, thermal switch and also the control board. We cut a 40mm hole in the plate and mounted the controller on 15mm standoffs so that the fan forces air through this hole. This plate also uses 50mm standoffs and mounts to the end of the plastic enclosure.

In both cases, secure the resistors to the plates using 10mm-long M3 machine screws, shakeproof washers and nuts. Add a little thermal paste under each resistor for good heat transfer.

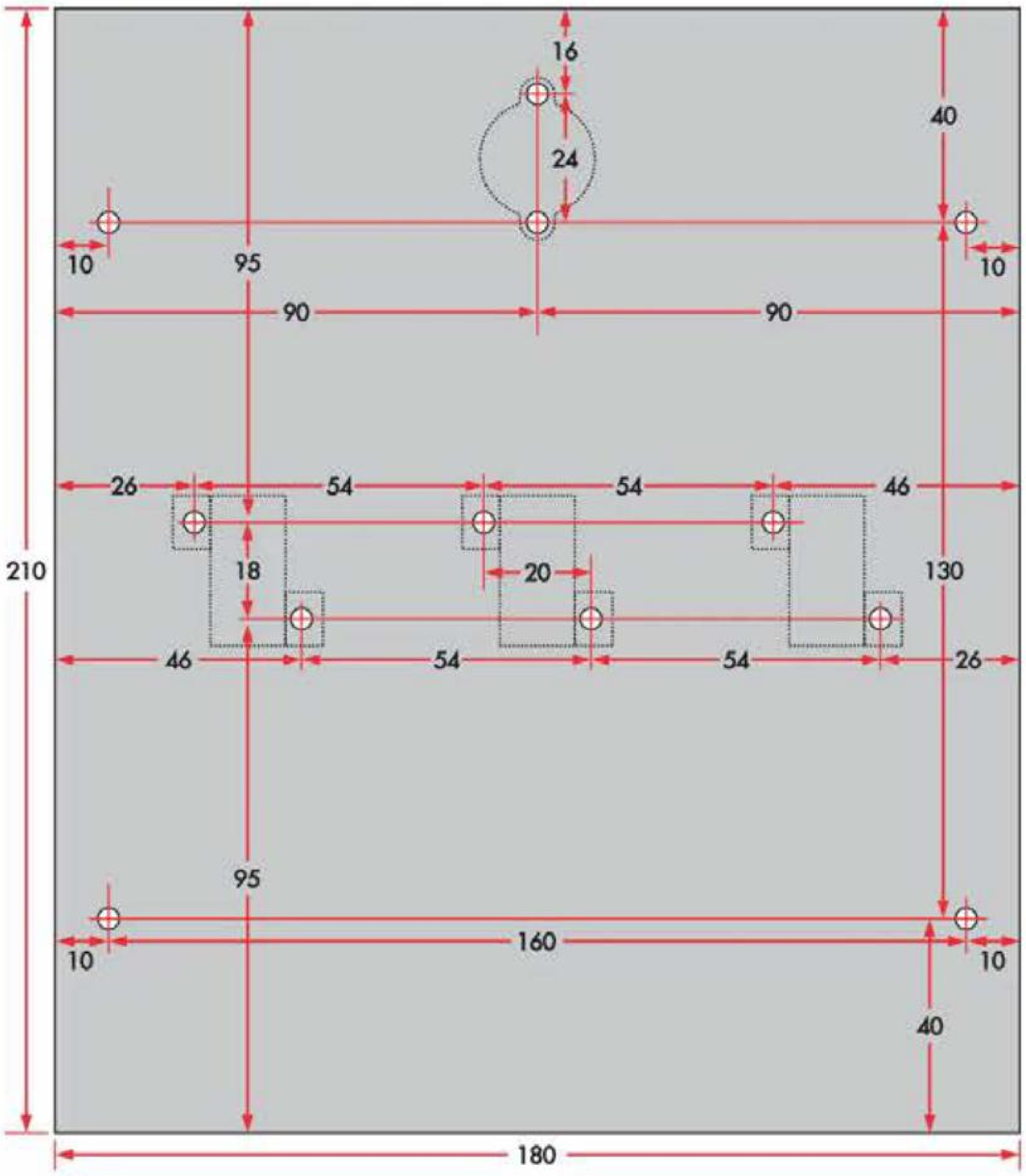


Fig.5: this plate for the plastic box holds just three power resistors and the thermal cutout. All dimensions are in millimetres.

ALL HOLES: 4mm DIAM.

SCALE: 50%

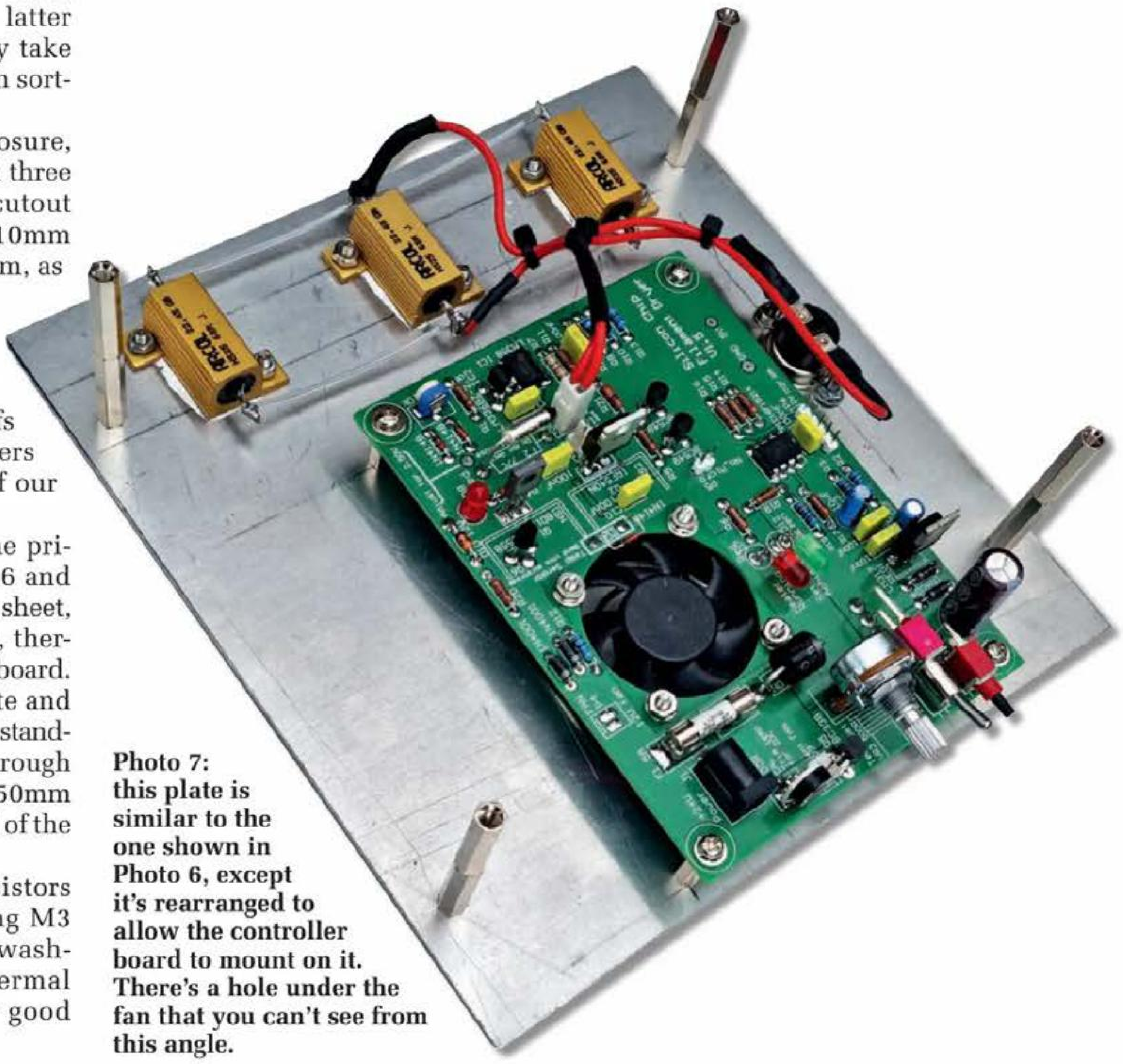
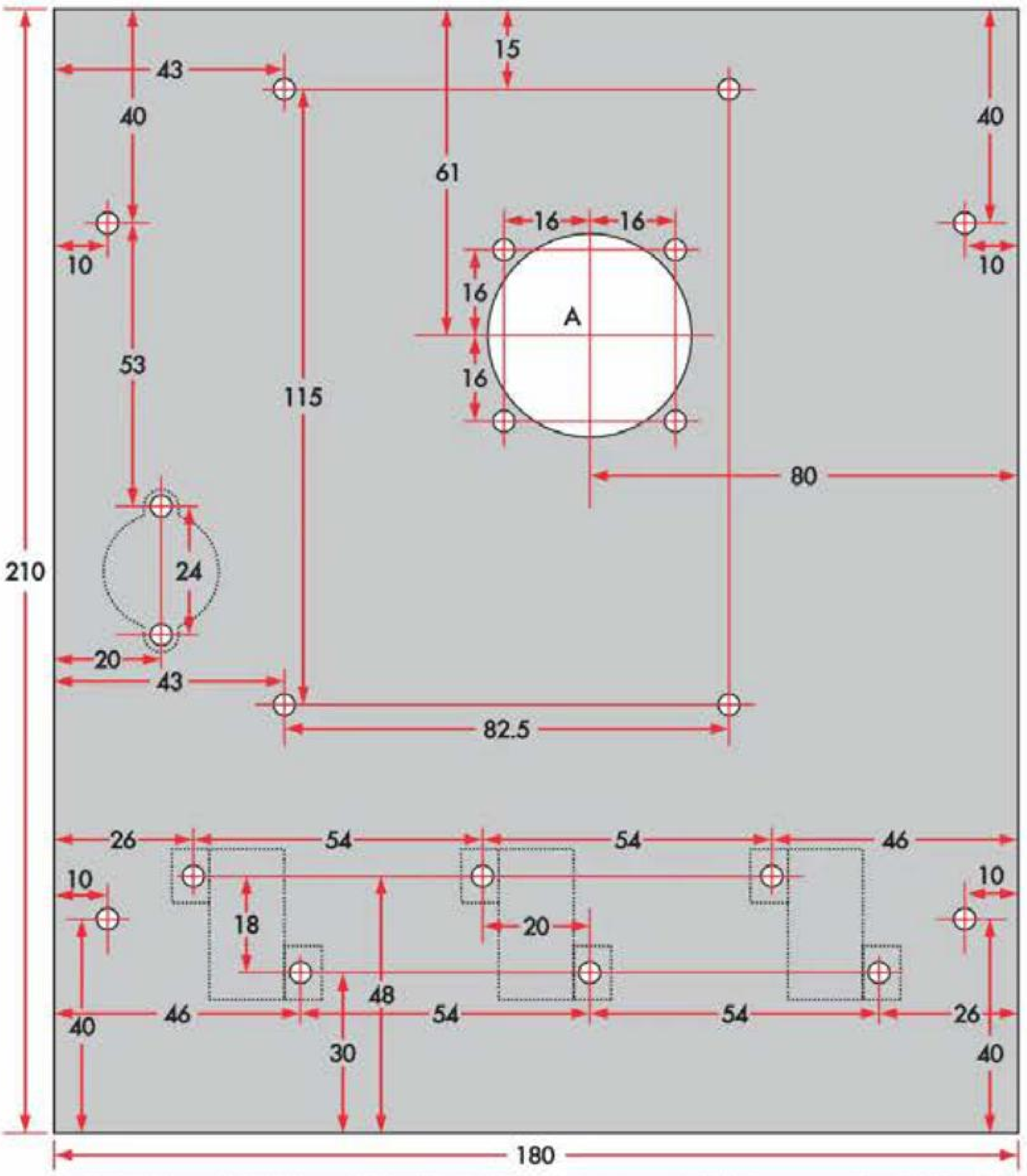


Photo 7: this plate is similar to the one shown in Photo 6, except it's rearranged to allow the controller board to mount on it. There's a hole under the fan that you can't see from this angle.


43
15
40
40
61
16
16
10
10
16
A
16
53
115
80
210
24
20
43
82.5
26
54
54
46
10
10
18
20
48
40
46
54
54
26
40
30
180

HOLES: 3mm DIAM. EXCEPT HOLE A: 38mm DIAM. SCALE: 50%

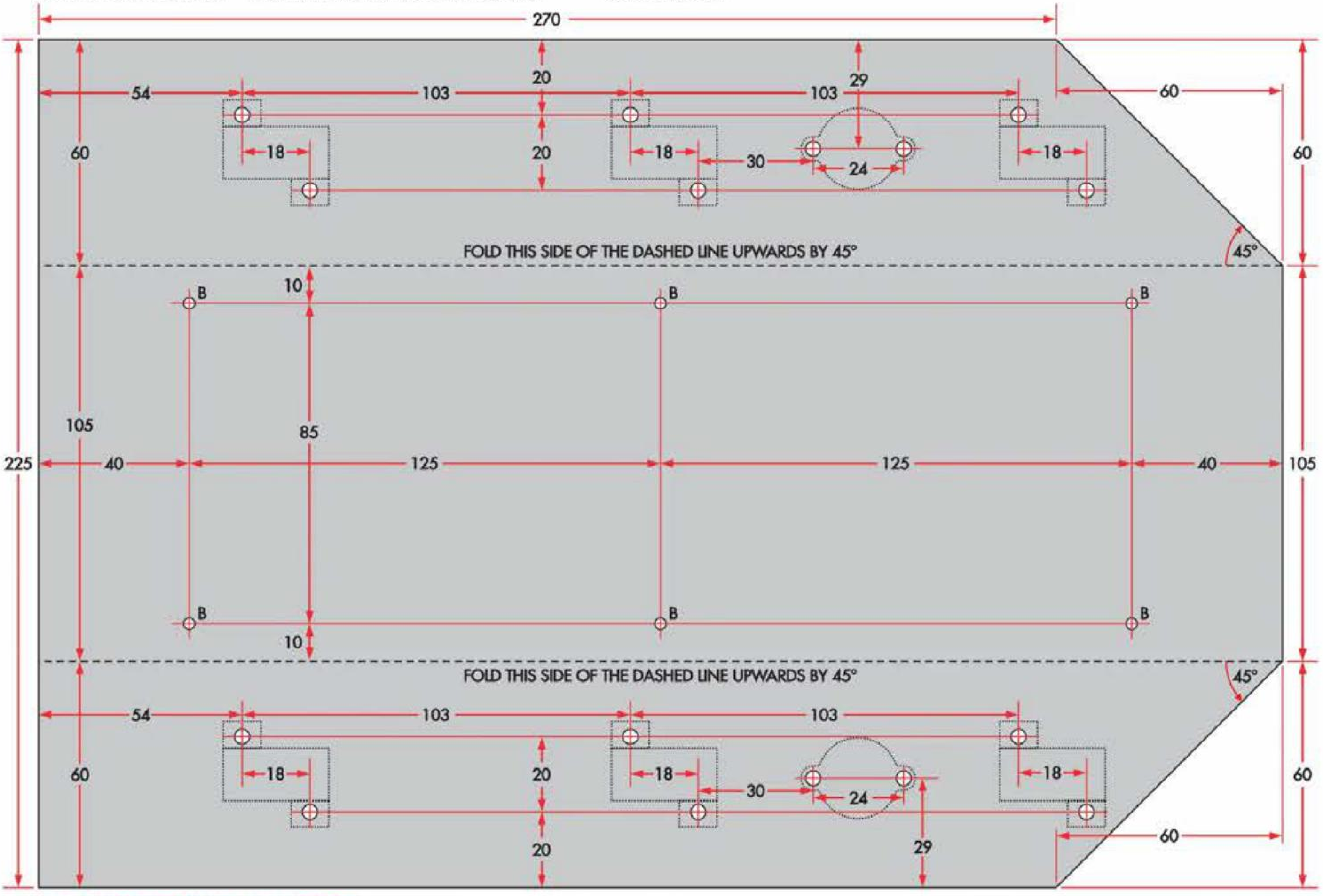
Fig.6: the second plate for the plastic box is similar to the first, except that the controller board also mounts on it, with a hole for the fan's airflow to pass through.

We use a single large heat plate measuring 330 × 225mm for the timber enclosure, as shown in Fig.7 and Photo 8. This sits in the base of the enclosure.

To ensure there is good ventilation around this, we bent the outer 60mm of each side up at about 45° and screwed six 10mm standoffs on the underside of the flat part to act as feet. This creates a plenum under the entire plate and larger triangular plenums down the sides.

The ends of the plenum are cut off at 45° to create openings at the opposite end to the controller. We have mounted the controller so that it draws air through this plenum. The six resistors are mounted three on each side of the plate, on the underside, so they are protected from people's fingers and stray material.

We also mount 90°C thermal switches on either side of the plate to protect against overheating. In all our testing, we did not manage to trigger these switches, but they are an important failsafe. Do not omit them.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ALL DIMENSIONS IN MILLIMETRES ALL HOLES: 4mm DIAMETER, EXCEPT HOLES B: 3mm DIAMETER SCALE: 50%

Fig.7: the heater plate for the custom box has all six power resistors mounted on it, three on each side, with each triplet having its own over-temperature cutout. The six holes in the middle are for standoffs to space it off the bottom of the box.

We made a lid for the timber enclosure from two sheets of acrylic (not included in the parts list). One is cut to the full size of the box, and a second is cut so it fits neatly inside the box. By mounting these to one another with 10mm spacers (we drilled straight through both sheets, ensuring an exact alignment of holes), we achieve a poor person's 'double-glazed' lid, which self-aligns itself when you put it on (see Photo 9).

The box

Your approach to the box will depend on how handy you are in the workshop and how much time you want to spend. We will show two examples of how it can be made, one from 12mm plywood and the other using an 18L storage box from our local hardware shop. To reduce heat loss, you need to install Correx insulation in both versions.

If you chose a smaller plastic box, you would have less heat loss and be able to achieve a higher temperature and/or reduce the power consumption.

We will leave this to your creativity. We certainly would not go any larger than the 18L box we used.

We used some offcuts of 12mm plywood for our timber box and made a rod to hang four 200mm diameter filament reels inside. While there is no standard, most manufacturers seem to be settling on this as the size of a 1kg reel. We added a baffle inside the box that allows us to force air circulation through it. It also ensures that our controller is protected from any rough handling of the reels.

Because we used timber, which is not moisture-proof, we gave the box two coats of varnish. We used polyurethane varnish, but any paint will do, so you can make it any colour you like. Check the paint you're going to use to see if you need to seal and/or prime the timber before applying it.

Our design includes provision for a rail on which you can hang up to four reels of filament. We 3D-printed the hanger hooks; the STL files for these and the other 3D-printed parts used can be downloaded from: siliconchip.au/shop/6/484

These suit 22mm diameter or smaller timber dowel; ours was pinched from an old broom handle. We also made

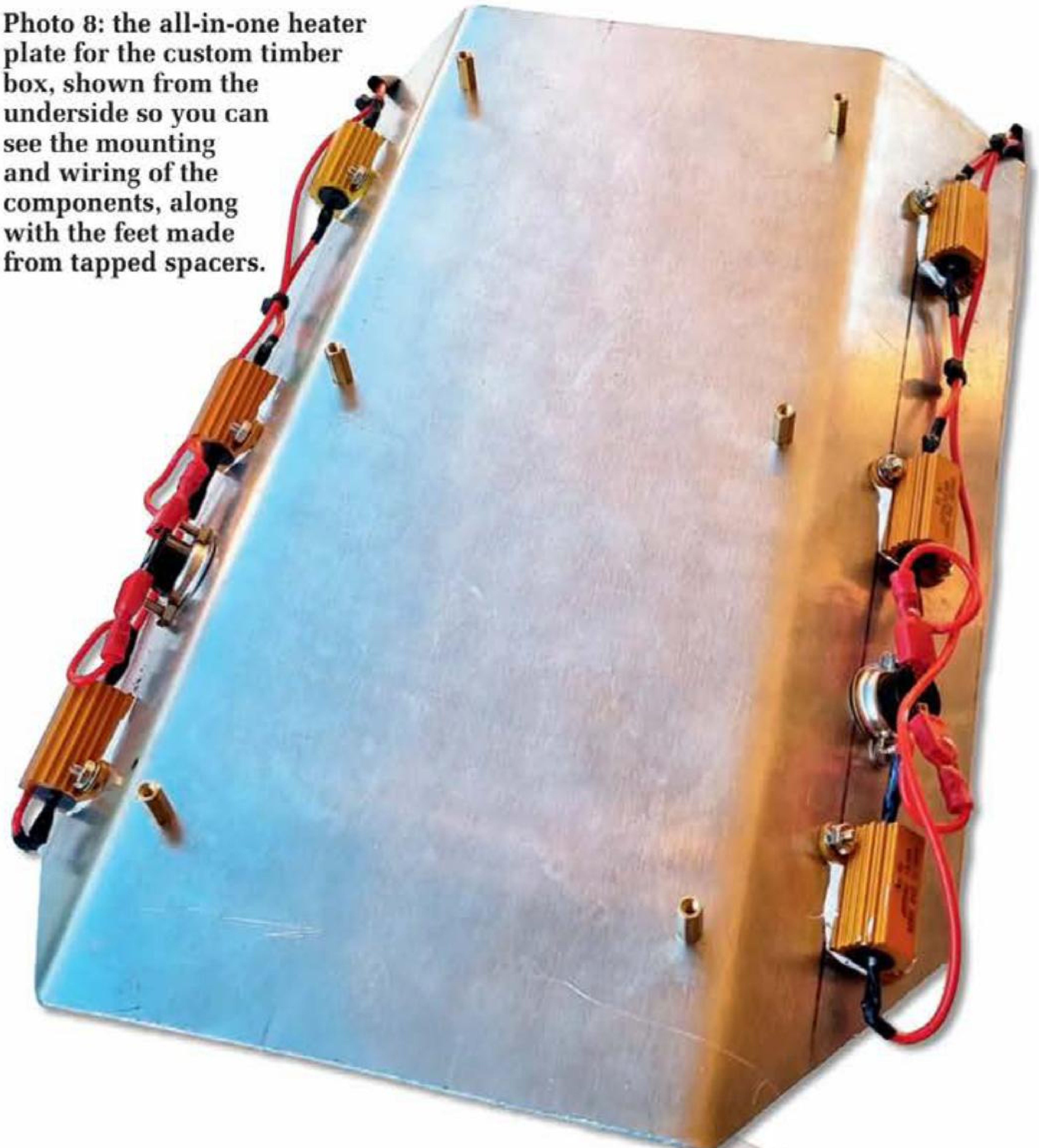


Photo 8: the all-in-one heater plate for the custom timber box, shown from the underside so you can see the mounting and wiring of the components, along with the feet made from tapped spacers.

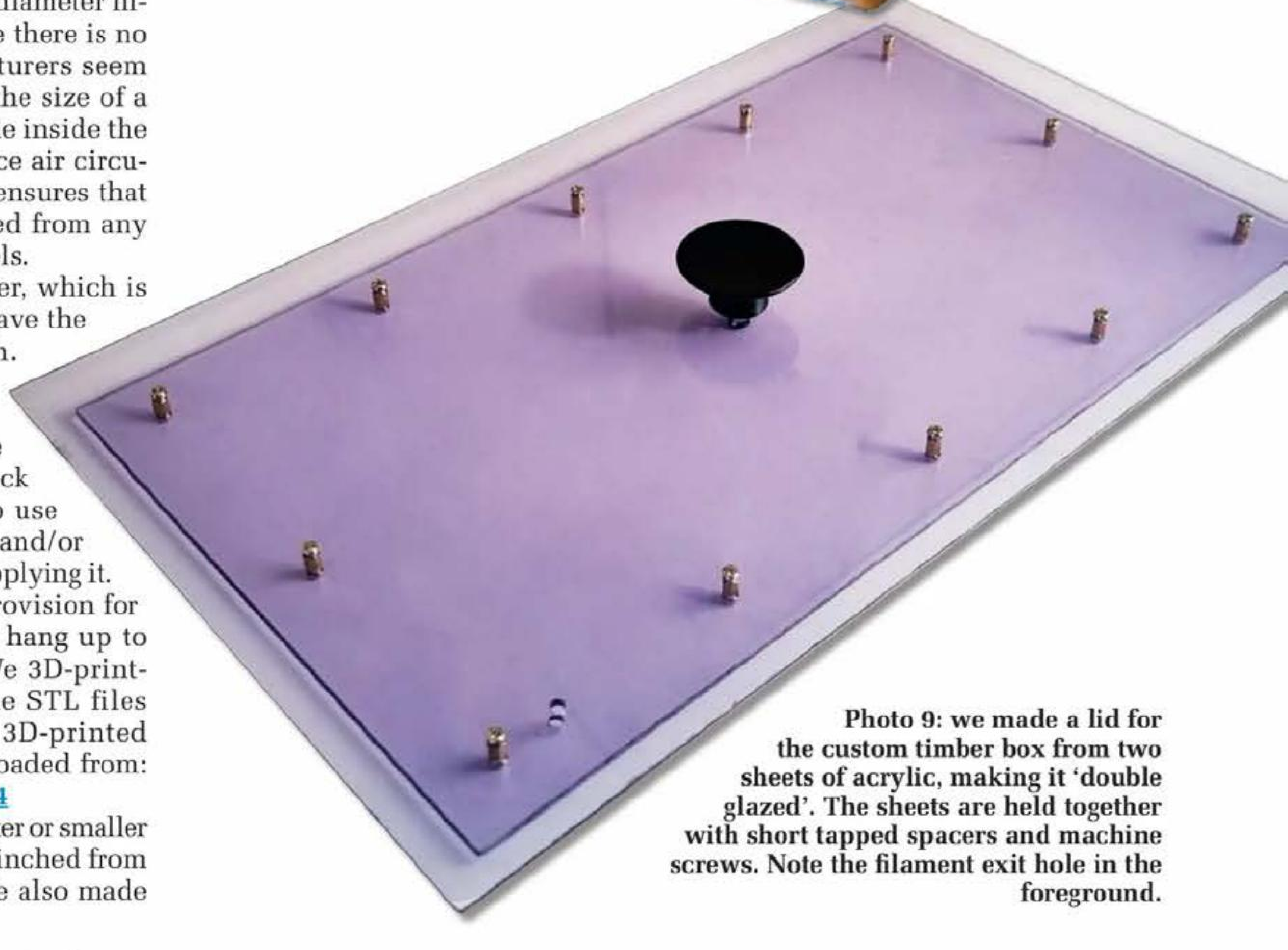
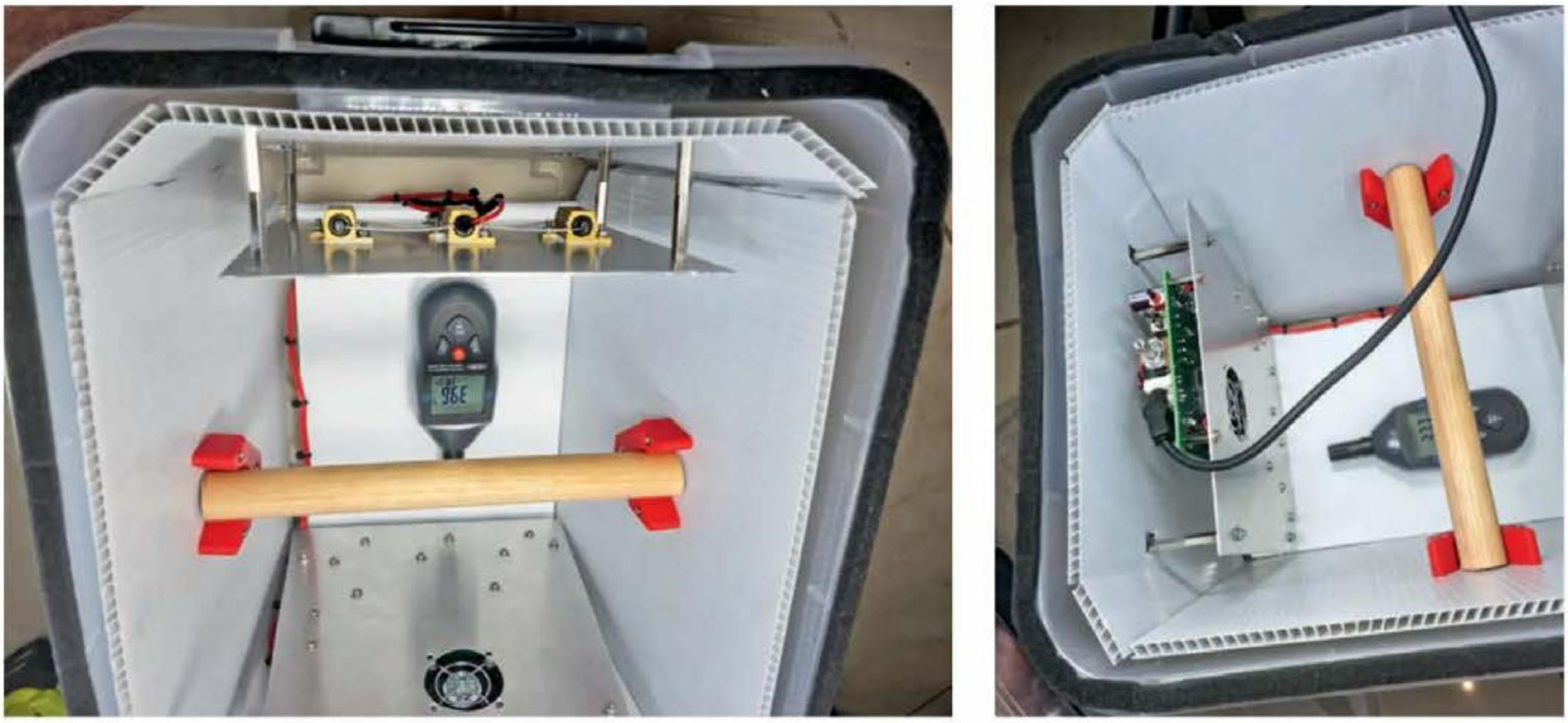


Photo 9: we made a lid for the custom timber box from two sheets of acrylic, making it 'double glazed'. The sheets are held together with short tapped spacers and machine screws. Note the filament exit hole in the foreground.



Photos 10 & 11: these photos show the locations of the two heat plates and controller in the plastic case. Note how the dowel is held in place by two red 3D-printed brackets to make it easy to add and remove reels.

ventilation covers, one for the exit and one for the ventilation fan (the ventilation fan should be installed in a hole in the outside of the box). Both of these allow you to close the vent. The STL files for these are in the same download package.

We used long screws to secure the vent fan cover to the case; you could use superglue instead.

We have included some simple drawings of our timber box in the download package, but we expect readers to have their own spin on it. Again we note that the box we built is right at the upper limit of what we would suggest you build; making it shorter would reduce heat loss.

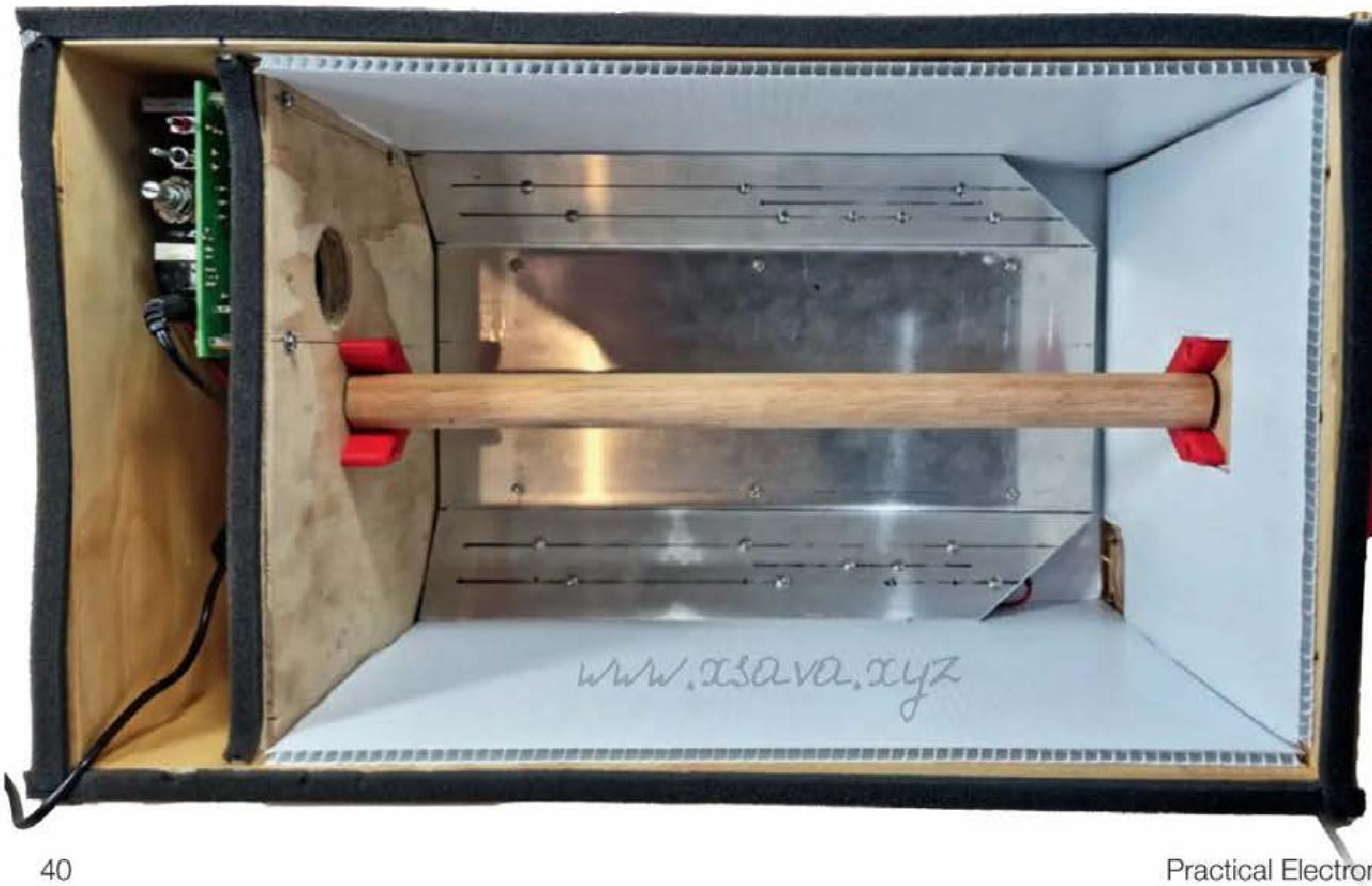
Insulation

For the plastic box, we cut 'insulation panels' from polypropylene Correx material (fluted polypropylene board). We chose this as it is easily cut, includes air pockets for insulation and does not present a fire hazard at the temperatures we are working with.

The sidewall insulation pieces are 270mm wide at the base, 290mm wide at the top and 235mm high. The end wall insulation pieces are 200mm wide at the top, 180mm wide at the base and 235mm high. The side flaps are 10mm wide at the base and 35mm wide at the top. The bottom layer insulation sheet is 280 × 170mm.

Foam tape must be applied around the top lip of the box to improve the seal on this enclosure. It makes a huge difference to the system's performance. We found it increased the temperature inside the box by 4°C for the same power input (tested at 34W).

To justify the need for insulation, we tested the performance with and without insulation. With 50W continuous dissipation in the insulated box, it reached 50°C (22°C ambient),



www.xsava.xyz

Photos 13 & 14: here you can see the finished custom timber box, with 3D-printed parts holding up the dowel from which the filament reels hang. This box can handle four 1kg reels. The Corflute insulation on the sides and the foam tape to seal the lid are essential for good performance. The controller is mounted in the section, behind the baffle panel, with a hole for the fan to push air through.

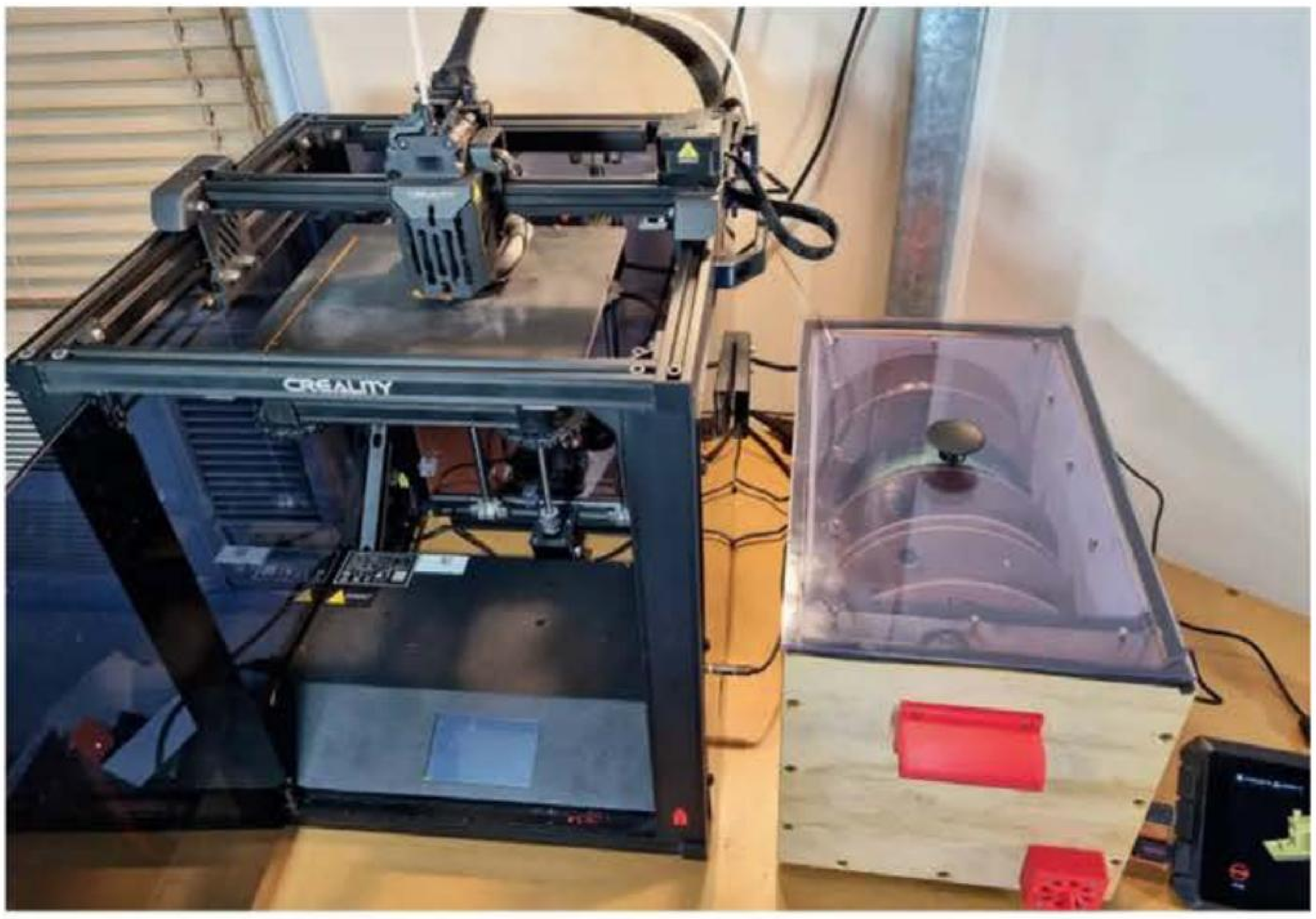


Photo 12: the finished Filament Dryer in the custom timber case connected to a Creality 3D printer.

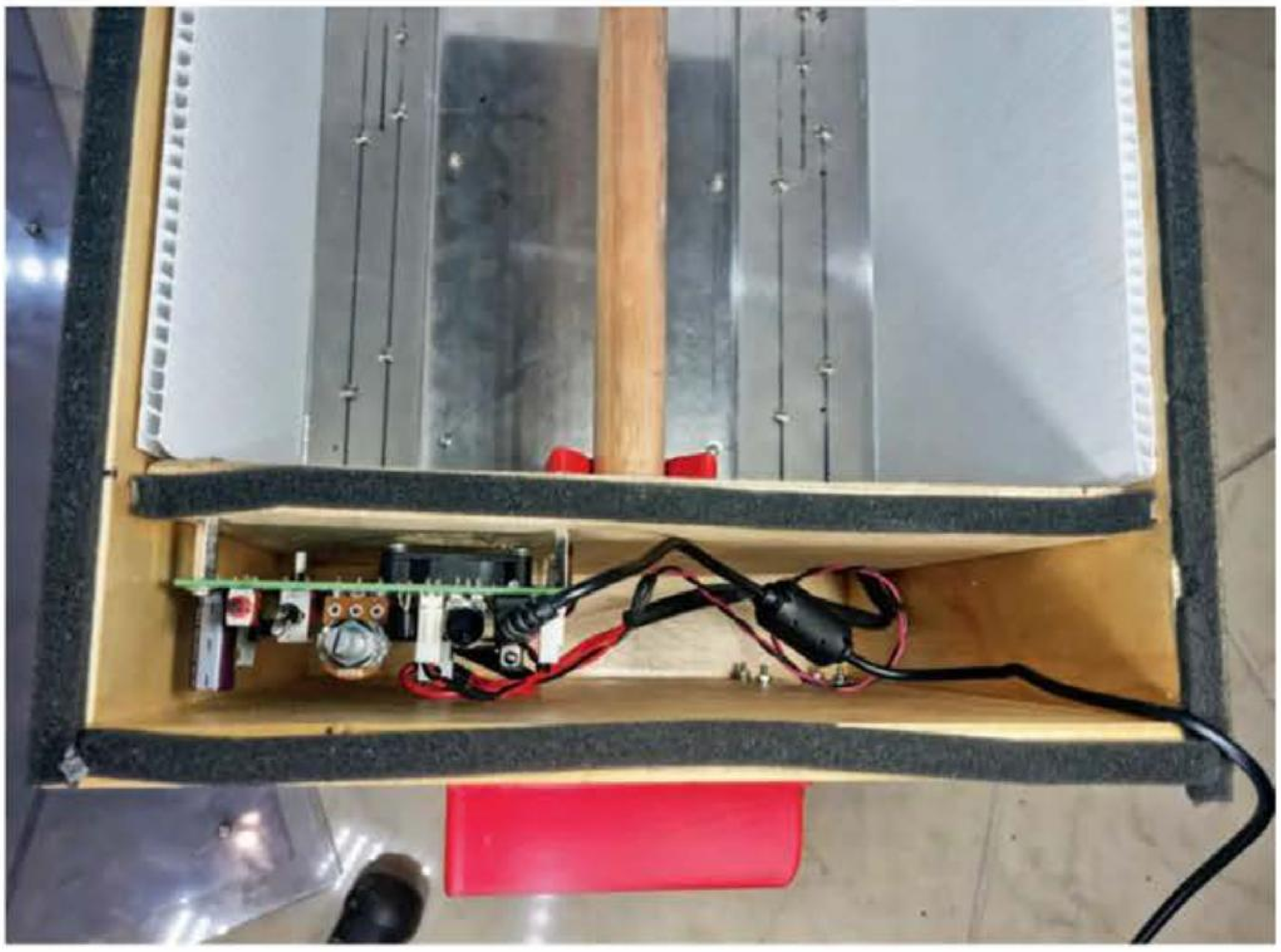
while without insulation, it only reached 41°C at the same power level. The Correx insulation and foam seal for the lid together save around 20W during operation.

You should insulate the timber box similarly, but the dimensions of the pieces will depend on the exact size of your box. Once insulated with Correx, the timber box's performance was pretty much identical to that of the plastic one, reaching 50°C with 50W of dissipation or 41°C at 32W.

Using the Dryer

Using the Dryer is really simple. You thread the reels you want to dry onto the rail and hang them in the Dryer. Secure the lid and press the Start button with your selected temperature (set with VR3) and time (set with S1; up [away from the PCB] is six hours and down [towards it] is nine). We prefer to turn the temperature up to 50°C and allow the controller to take over from there, but almost all our printing is done with PLA.

We hope that the discussion of safety & implementing controls in the design has led to some consideration of where and how safety in design plays a role in your hobby. PE



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Brilliant to the bone

Techno Talk

Max the Magnificent

From bone-conduction headphones to exploring RealSense's depth cameras and Eyesynth's futuristic NIIRA headset, this month we journey into sound, vision and accessibility technology with life-changing potential.

I mentioned this last month but, as a reminder, earlier this year the folks at H2O Audio (h2oaudio.com) gifted me a pair of their TR2 multi-sport, waterproof bone conduction beauties, which even work underwater if I want to listen to music while swimming.

I must admit that before actually taking these for a spin, I had wondered about the quality of sound that can be achieved using bone conduction technology. I can honestly say that they exceed my expectations. To my untrained ear, the sound quality is as good as that offered by my regular headphones.

Of course, they don't block out external sound, but that's an advantage in many situations. For example, when my wife (Gigi the Gorgeous) and I recently visited her mother, who lives in Nashville, Tennessee, I spent a delightful couple of hours trailing them as they meandered their way around a series of stores.

I say "delightful" because I was happily enjoying a science fiction audiobook while still being able to detect and respond to the occasional dulcet tones directed at me by my spouse.

They're also great if you're on a bicycle, scooter or similar, or even just walking around the streets, as you can still hear vehicles approaching, sirens and so on. Wearing them allows you to listen to music, audiobooks etc without ruining your situational awareness.

Similarly, bone conduction technology offers an ideal solution for audio aids intended for the visually impaired, who rely on being able to hear what's going on around them. We will return to this in a moment, but first…

RealSense's D415

A few days ago, I had a very interesting chat with the folks from RealSense (realsenseai.com). This used to be a division at Intel, but they recently spun out to begin operating as an independent company.

Their primary focus (no pun intended) is computer vision technologies, particularly depth-sensing systems, that enable machines to perceive and understand their environment. One example of this is their D415 Depth Camera.

There's much more to this than meets the eye (OK, pun intended this time; sorry). Let's start with the two RGB+ cameras mounted on the left and right sides (I'll explain my use of the '+' qualifier in a moment). These are used to provide stereoscopic depth perception in much the same way as human binocular vision.

Each camera captures the same scene from slightly different angles. By identifying matching features in both images, the system measures their horizontal displacement, called disparity. Nearby objects show a significant disparity, while distant ones show little.

Using triangulation, the system converts disparity into depth, producing a 3D depth map where each pixel encodes distance. This enables applications like object detection, robot navigation, augmented reality and gesture tracking.

This is the clever bit. If we were to use regular RGB cameras, their performance would be degraded by poor lighting and low-texture surfaces, such as a flat white wall. The CMOS sensors used in RGB cameras are sensitive to a broad spectrum, including infrared (IR). If left unchecked, this IR can 'bleed' into the RGB channels, resulting in strange, washed-out colours.

That's why traditional RGB sensors include an IR-cut filter to remove the IR component from the image. The RGB+ cameras in the D415 don't have this filter, meaning they also pick up infrared light, hence the '+'.

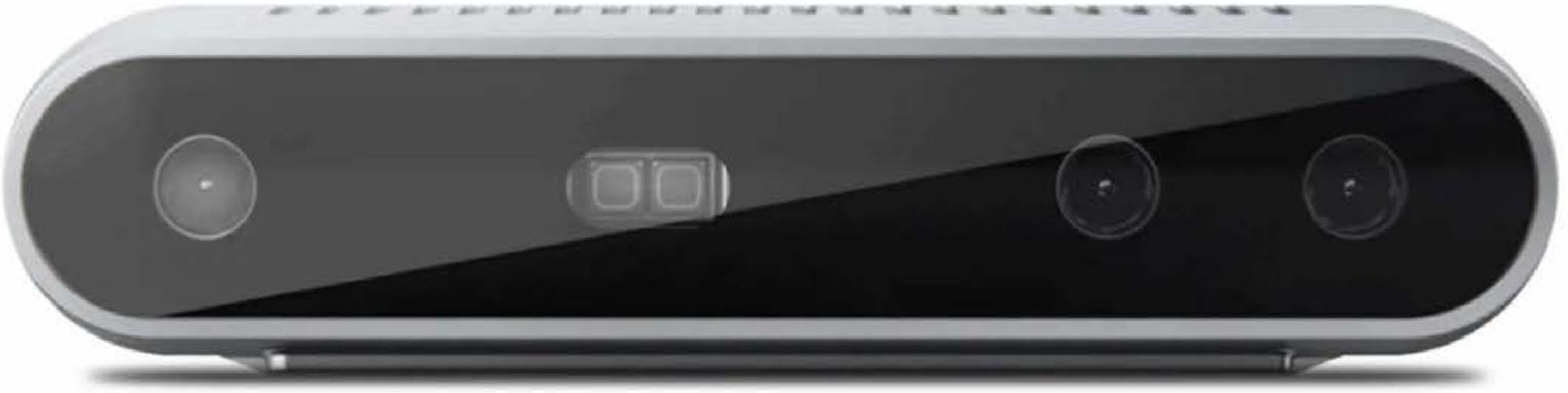
Now observe the big 'thing' to the left of centre (I hope I'm not being too technical). This is an IR projector that casts a random pattern of thousands of dots, allowing the system to generate a 3D depth map even in a dark room and/or when viewing a flat, unicolored surface, such as a painted wall.

The other 'thing' to the right of centre is a regular RGB camera. This captures a traditional RGB image of the scene. This image is 100% aligned with the 3D depth map, frame by frame and pixel by pixel. The D415 makes this data available for use by other people's applications and systems (robotics, industrial automation, 3D scanning and modelling, medical imaging, motion tracking etc).

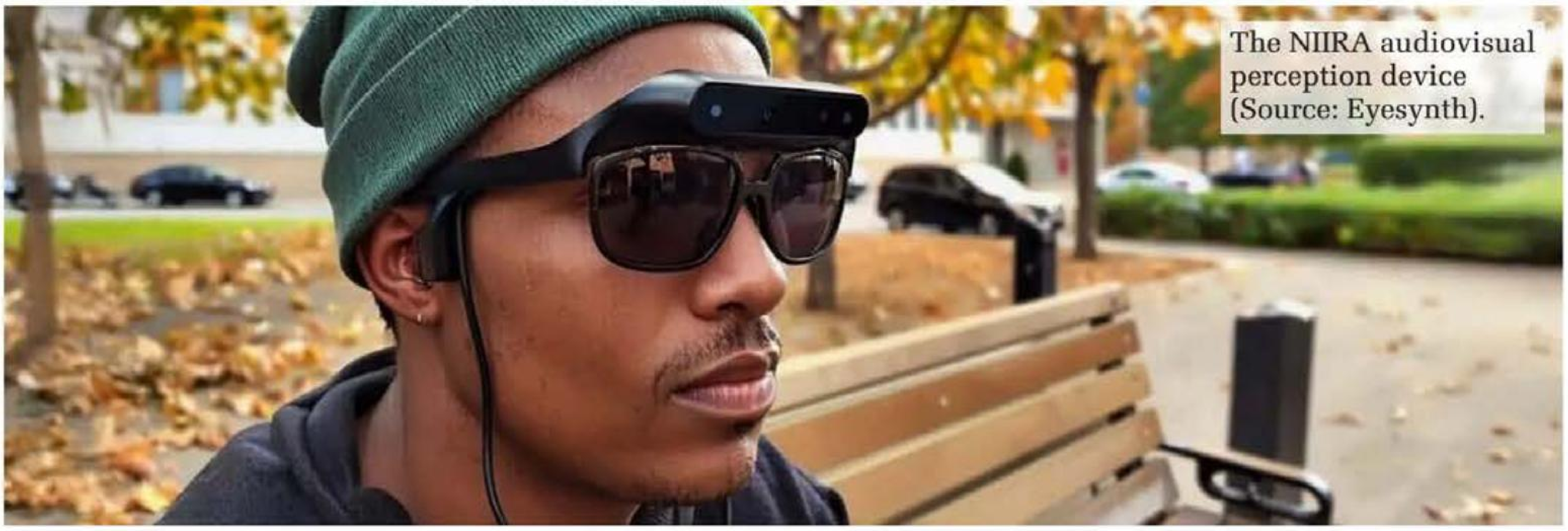
Speaking of which…

Eyesynth's NIIRA

One application that really (I'm going to resist saying "caught my eye") attracted my attention is the NIIRA audiovisual perception headset from Eyesynth (eyesynth.com). If you look closely at this device, you'll see it



The D415 Depth Camera (Source: RealSense).



The NIIRA audiovisual perception device (Source: Eyesynth).

has a RealSense D415 depth camera seamlessly moulded into the frame above the lenses. This headset connects to a small AI computer, roughly the size of a pack of playing cards.

The RealSense D415 delivers the raw perception layer, and the Eyesynth NIIRA system adds the intelligence, interpreting the 3D scene, performing object detection, recognition, and contextual analysis. Any relevant information is translated into soundscapes that are conveyed to the user via the NIIRA bone-conduction audio system.

As we previously noted, people with visual impairments rely heavily on sound cues from their surroundings. The last thing they want is to block their ears with headphones or diminish their hearing with earbuds, hence the use of bone conduction technology.

My cousin Graham

My cousin Graham is three years older than I am. That means he knew much more than I did when we were younger. I know this to be true because he told me so. He also told me that spaghetti was made from peeled worms, which has left a bad taste in my mouth to this day.

About 30 years ago, Graham started to lose his sight. He's now totally blind, but that hasn't slowed him down. He danced with gusto and abandon at my wedding; he hosts a local radio show; and he often attends concerts in the city centre, making his way there and back again by bus and on foot.

A few years ago, I was invited to give a talk on advanced technologies at Sheffield Hallam University. Knowing Graham's interest in this sort of thing, I invited him to attend.

A lot has changed since I was a student there. I graduated in 1980. Goodness gracious me. I just realised that was 45 years ago. I'm too young for all this excitement!

The thing is that I got lost on the way to my designated lecture theatre. I found myself standing at an intersection of corridors whose layout would have made the designer of the Paris street system blush with pride.

I was confused, which is my natural state, so at least I was playing to my strengths. Then I heard a "tap tap tap" sound, and Graham appeared from around a corner, striding confidently along. I'm embarrassed to say that it was Graham who led us to our destination.

If I ever win the lottery, I think it's safe to say that Graham will find a NIIRA audiovisual perception device lurking in his Christmas stocking.

Me aged ~3 (left) and Graham aged ~6 (right).

Circuit Surgery

Regular clinic by Ian Bell

Measuring the frequency response of a circuit or device using a PC sound card, part 2

Last month, we started discussing how to measure the frequency response of a circuit or device. This was motivated by the need to measure the response of the example digital filter from the recent DSP series, recognising that not all readers will have test lab equipment capable of this.

The alternative is to use the "sound card" (audio interface) of a computer or laptop to generate the input signal and analyse the response using software. Such programs are mainly aimed at measuring audio systems/acoustics, but can be applied to circuits acting on signal frequencies in the audio range (20Hz-20kHz).

In the previous article, we mainly focused on the basic principles of circuit frequency response of linear circuits such as amplifiers and filters, which we will recap briefly below. We also introduced use of PC sound cards to make measurements, concluding with a test set-up like that shown in Fig.1.

Here, we see one stereo channel used for measurements and the other for reference, but other configurations are possible.

Audio interfaces are limited compared to lab test gear in that they only generate and measure AC over a limited amplitude range. Therefore, the I/O signal levels, DC offsets and load drive capabilities for the device under test and sound card I/O may not be compatible. This may require signal conditioning circuits at either or both the input and output of the device, as shown in Fig.1.

That figure includes an audio amplifier that could be used to listen to the test signal. It can also be used to listen to the output from the circuit under test (connected in parallel to the sound card line input). I have used a switch set-up to enable easy comparison of the two signals.

If you do set up the capability to listen to test signals, be careful and keep volume levels low. Test signals are not pleasant to listen to and have more potential to damage your speakers or even your ears than standard audio recordings.

A recap of the key concepts

For a linear circuit with input X and output Y, we write $Y(f) = H(f)X(f)$, where H is the transfer function – the relationship between the input and output of a circuit. The signals and transfer function vary with the frequency, f. The term "frequency response" often refers to graphs showing how the transfer function $H(f)$ varies with frequency.

Each point on the graph represents a single frequency, which implies a steady state (infinite duration) sinusoidal input, and linearity implies a sinusoidal output. At each frequency, the output waveform may be shifted in time and may have a different amplitude with respect to the input.

The time shift is usually expressed as phase shift – the proportion of the cycle time ($1/f$) of the waveform at the frequency of interest (f), typically in degrees.

The fact that two aspects change from input to output (amplitude and phase) means that H at a given frequency cannot be represented by a single number.

We can use the polar form of gain magnitude/phase angle, which is what is shown on the Bode plot. Alternatively, signals and transfer functions can be represented with a Cartesian format using complex numbers, which facilitates mathematical circuit analysis. Still, this advanced maths is not essential knowledge for basic frequency response measurement.

To measure a frequency response, we can apply a sinewave input, wait for the circuit to stabilise (steady state approximation), measure the input and output amplitude and phase difference, then repeat for as many frequencies as required. This is straightforward, can be implemented manually (with a signal generator and dual channel oscilloscope), but is relatively slow.

Alternatively, other inputs, such as sinusoids that are swept continuously in frequency, or various types of wideband noise, can be used. The frequency response results are obtained by mathematical analysis of the measured

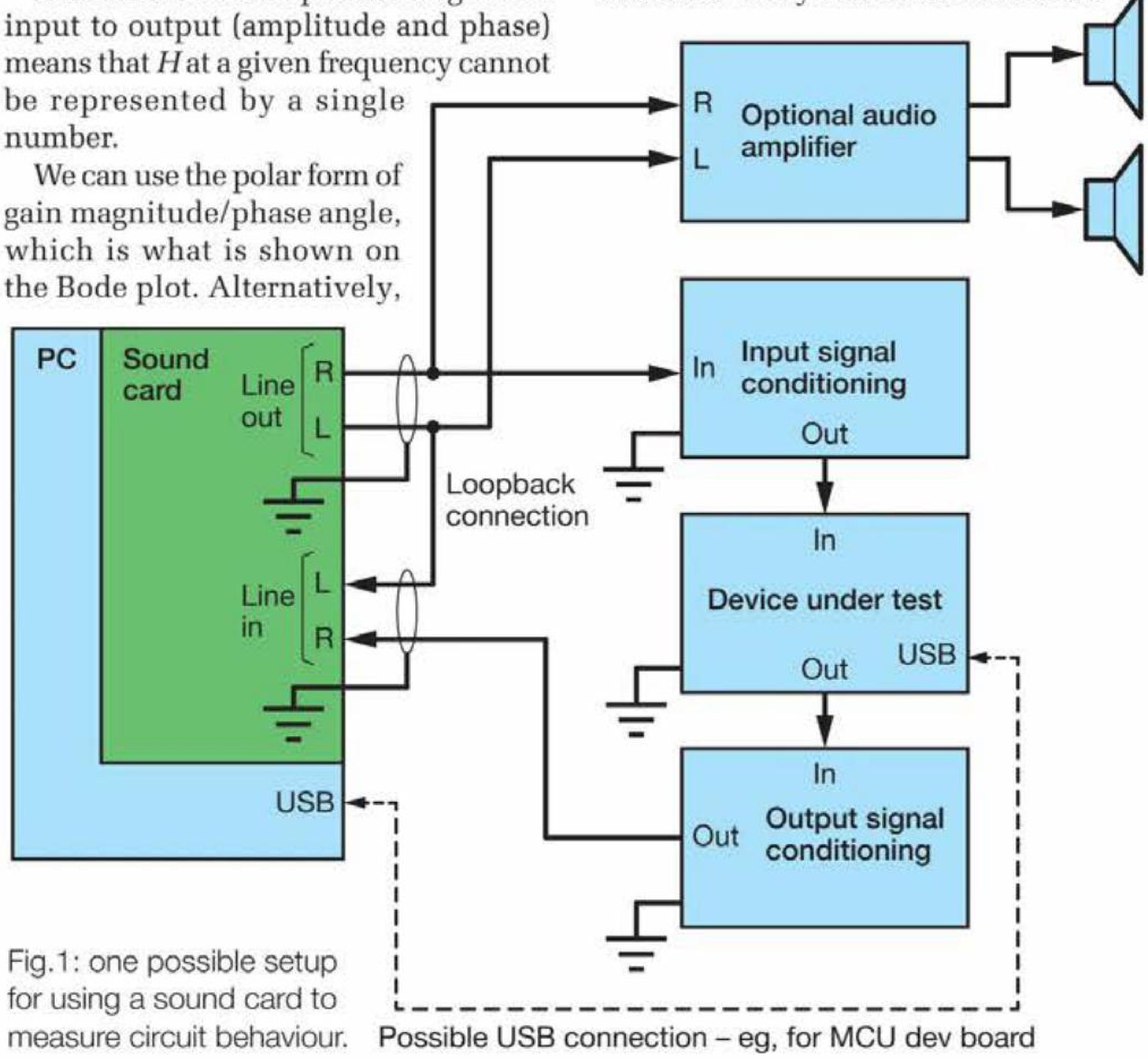


Fig.1: one possible setup for using a sound card to measure circuit behaviour.

response; for example, using a fast Fourier transform (FFT), rather than simple individual measurements.

In this case, the instrument or app does the maths for you to calculate and present the results. Still, some understanding of the theory will help when choosing settings/preferences and interpreting the results.

An introduction to REW

Prior to writing these articles, I had not made extensive use of sound card apps for circuit measurement, so this article covers my experience and experiments so far. I have tried a few programs, but have spent most time using one called Room EQ Wizard (REW), so it will be the focus of this article.

I cannot claim to be a REW expert, but I have obtained some useful results. I may look at other features and other apps in the future.

REW is aimed at room acoustic measurement, loudspeaker measurement and audio device measurement. For example, to help optimise the acoustics of a listening room, studio or home theatre and find the best locations for speakers, subwoofers and listening positions. Having said that, its use for electronics is recognised by the developer.

Some of its extensive measurement capabilities, including for frequency response and distortion, are useful for circuits via a setup such as the one shown in Fig.1. Others, such as reverberation time (RT60) are more specifically acoustics-related.

REW is available as a free download from **www.roomeqwizard.com** for Windows, macOS and Linux. I have only used the Windows version. REW is supported by donations, but there is also pro upgrade available for a one-time fee that provides multiple-input measurement capabilities. At the time of writing, the current version is 5.31 (released in 2024).

REW was created by John Mulcahy over twenty years ago, and he has continued to develop it since then. Originally, REW was mainly focused on setting up equalisers, but its measurement capabilities have been extended over the years. It is still under development, with various beta releases of version 5.40 published over recent months.

If I understand it correctly, a key new feature in this future version is an application programming interface (API) which will, for example, allow advanced users to integrate their own code with REW, to make use of its measurement or calculation capabilities.

REW is a complex piece of software with many features, settings and capabilities. As such, it may present a steep learning curve for new users. However, it has comprehensive documentation (in the program, via tooltips and online), which provides a good introduction to getting started and using the software.

This seems to reflect a philosophy of making software suitable for both enthusiasts and professionals (indeed, it is used by both). The main preferences dialogs include help text in the window, which means you don't have to search separately to find out what the settings do.

There is also an active support forum on the AV Nirvana website (**https://pemag.au/link/ac8k**).

It is recommended that new users read the first few sections of the help before jumping to more specific details. I will cover some key points here to provide an overview of REW's relevant capabilities, and explain how I used REW for circuit measurements. Of course, I will not fully describe all aspects of the software.

Different information may apply to different computers, operating systems and audio interfaces, so you may need some details which were not relevant to me.

Units and levels

Various units of measurement will be encountered in REW (and other software and instruments making similar measurements), so it is worth defining what these mean before proceeding with discussing its use.

For testing circuits, we also need to be aware of the voltage levels of audio interface I/O, as this will determine compatibility with the device under test (DUT) and the design of any signal conditioning circuitry.

Signal levels in audio and acoustics are commonly expressed using decibels (dB); for example, in dBV or dBu units. Decibels express the ratio of two numbers, which is straightforward for gain, where we have an input and output level; for example, gain (in dB) = $20\log_{10}(v_{out}/v_{in})$.

For signals in isolation, we need to use a reference level to express the value in decibel form. For example, for a voltage signal, v_S, we need a reference level of v_0. The decibel value for the signal is then $20\log_{10}(v_S/v_0)$. For power (p) measurements, the decibel value is $10\log_{10}(p_S/p_0)$. If the signal value equals the reference, the level is 0dB.

Consumer audio line levels are typically about 0.316V RMS (root-mean-square), which is 0.447V peak ($0.316V \times \sqrt{2}$) or 0.894V peak-to-peak (0.447V × 2) for a pure sinewave signal. A signal of 0.316V RMS can be expressed as -10dBV – that is, minus ten decibels relative to a reference level of 1V RMS. For an RMS signal voltage of v_S, the dBV value is $20\log_{10}(v_S)$.

In early audio systems, connections were made using matched 600Ω input and output impedances, which was based on the practice in early telephony systems. The reference level used here was based on the voltage required to deliver 1mW of power to a 600Ω load, which is 0.775V RMS ($V^2 \div R = 0.775V^2 \div 600\Omega = 0.001W$).

Voltage values referenced to 0.775V are expressed as dBu, where the u is for "unloaded", as modern audio systems do not use 600Ω matched loads, but the reference level has persisted in common usage. dBV and dBu reference levels differ by a factor of 0.775 (multiply or divide as appropriate).

Due to the log function, this translates to an addition or subtraction of decibel values, specifically of 2.21dB, as $20\log_{10}(0.775) = -2.21$. So, we have dBu = dBV + 2.21dB and dBV = dBu – 2.21dB.

Signal power can be expressed in dBm, that is, decibels relative to one milliwatt (1mW). If we are measuring voltages, we need to know (or assume) the load resistance the voltage is driving to calculate the power value.

Professional audio systems typically use higher voltages than consumer ones, with a nominal level of +4dBu (1.228V RMS, 1.736V peak for a sinewave). In both cases, there can be variation in levels between different products. Sound card outputs are often designed to be used as headphone outputs, so they may differ from standard line outputs.

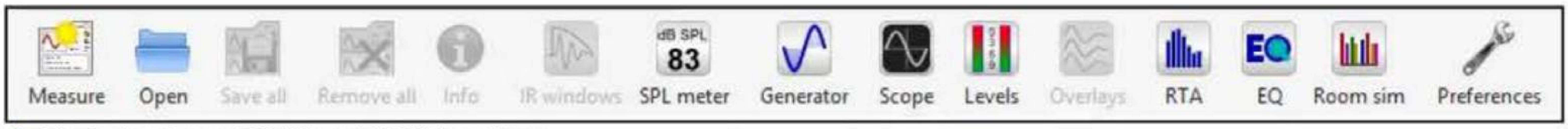
Full-scale levels

All signal processing systems have maximum input and output levels at which signal integrity is maintained. This is often slightly 'soft' – close to maximum, the signal quality will tend to decrease as distortion increases before a full limit (hard clipping) is reached.

For ADCs and DACs, there is a very specific hard limit set by the maximum numerical value that can be represented in the conversion – the full-scale (FS) value. Ideally, the analog circuitry associated with such a converter will not be too close to its limits at the converter full-scale, so the system as a whole will have a simple hard limit at the converter's full-scale value.

This full-scale value can be used as a reference for a decibel full-scale unit, denoted dBFS. dBFS is useful because we can immediately see how much headroom we have available to increase signal levels (eg, for a better signal-to-noise ratio), or cope with the highest input levels (eg, due to resonant peaks) without causing clipping in the measurement system.

Measurements in dBFS cannot be converted to other units using a generally applicable formula because the reference level depends on the specific hardware used and settings such as volume or gain controls. However, for a given setup


Measure
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IR windows
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SPL meter
Generator
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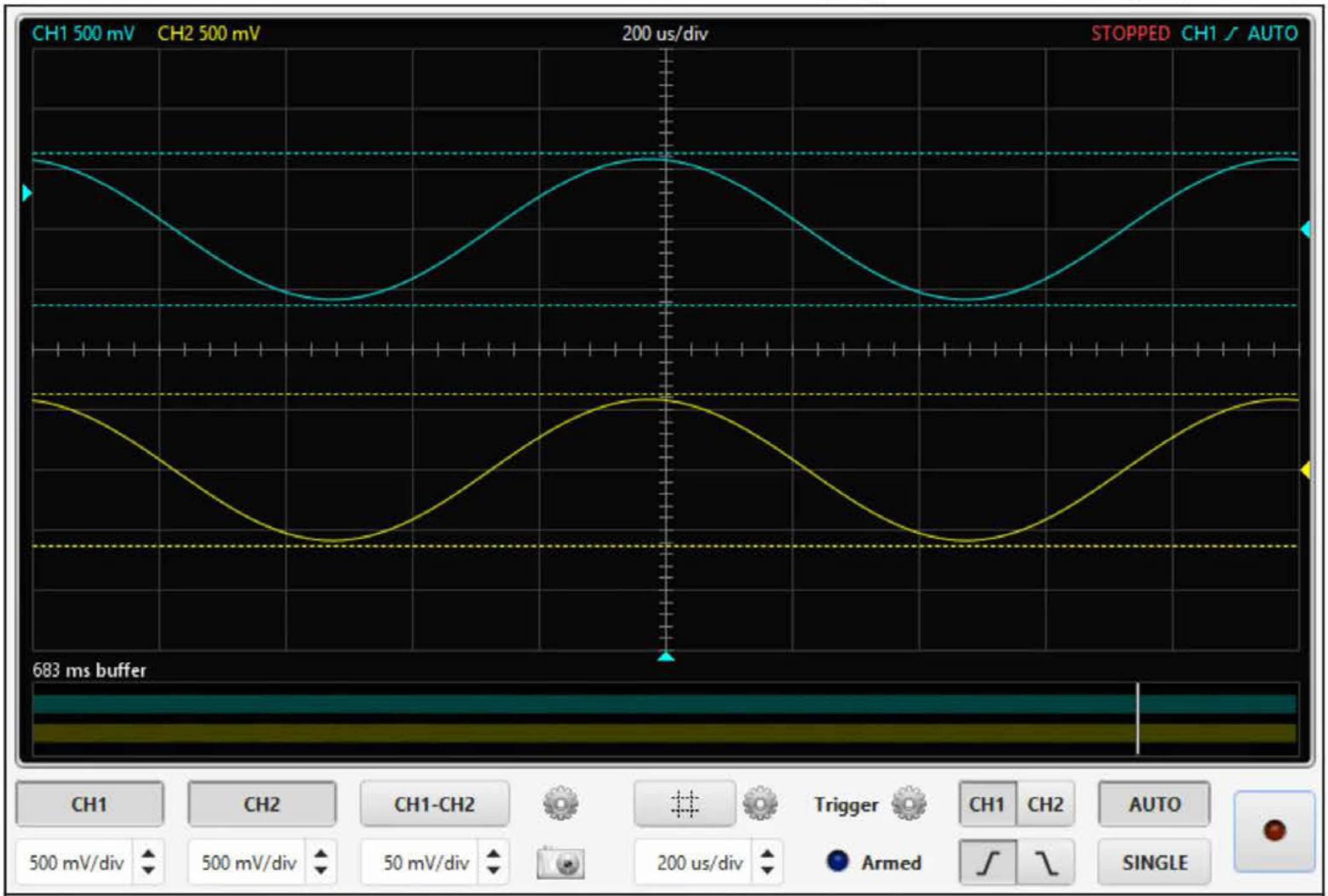
Levels
Overlays
RTA
EQ
Room sim
Preferences

▲ Fig.2: the Room EQ Wizard (REW) toolbar.

▼ Fig.4: the Room EQ Wizard (REW) oscilloscope.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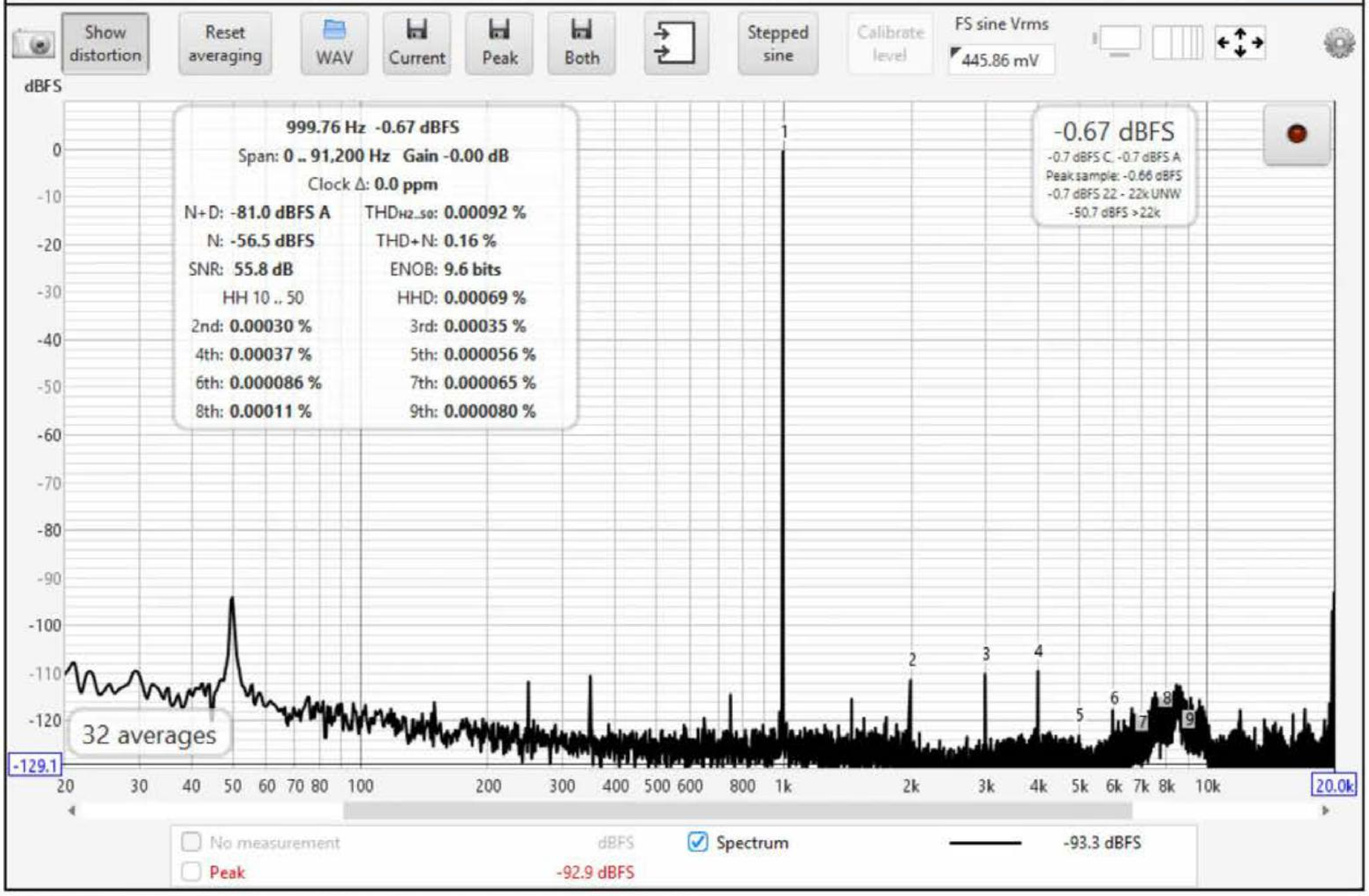
Show distortion
Reset averaging
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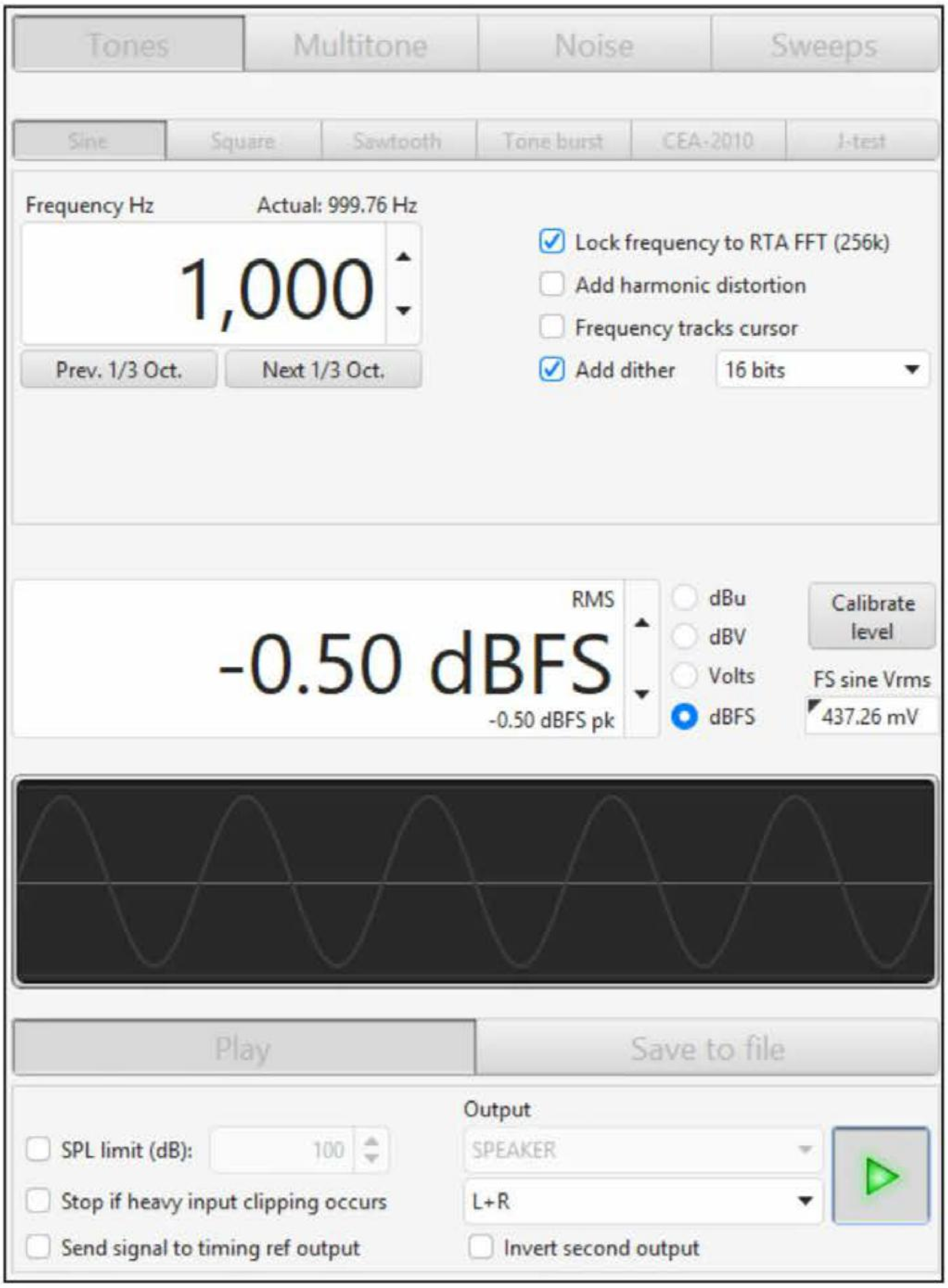
999.76 Hz  -0.67 dBFS
Span: 0 .. 91,200 Hz   Gain -0.00 dB
Clock Δ: 0.0 ppm
N+D: -81.0 dBFS A      THDH2..50: 0.00092 %
N: -56.5 dBFS          THD+N: 0.16 %
SNR:  55.8 dB          ENOB: 9.6 bits
HH 10 .. 50            HHD: 0.00069 %
2nd: 0.00030 %         3rd: 0.00035 %
4th: 0.00037 %         5th: 0.000056 %
6th: 0.000086 %        7th: 0.000065 %
8th: 0.00011 %         9th: 0.000080 %
```

```
-0.67 dBFS
-0.7 dBFS C, -0.7 dBFS A
Peak sample: -0.66 dBFS
-0.7 dBFS 22 - 22k UNW
-50.7 dBFS >22k
```

```
☐ No measurement         dBFS     ☑ Spectrum        -93.3 dBFS
☐ Peak                -92.9 dBFS
```

Fig.5: the Room EQ Wizard (REW) real-time spectrum analyser (RTA).



Frequency Hz 1,000 Actual: 999.76 Hz

☑ Lock frequency to RTA FFT (256k)
☐ Add harmonic distortion
☐ Frequency tracks cursor
☑ Add dither 16 bits

RMS -0.50 dBFS
-0.50 dBFS pk

○ dBu
○ dBV
○ Volts
● dBFS

FS sine Vrms 437.26 mV

☐ SPL limit (dB): 100
☐ Stop if heavy input clipping occurs
☐ Send signal to timing ref output

Output SPEAKER
L+R
☐ Invert second output

Fig.3: the Room EQ Wizard (REW) signal generator controls.

where the full-scale voltage is known, the conversion to or from other units is straightforward.

REW makes use of dBFS values and has the means to calibrate the reference value (define the full-scale voltages). For frequency response plots, it can use the relative input to output dBFS levels to plot transfer functions (denoted as dBr), or the voltage levels (V/V in dB).

Tools and measurements

When REW opens, it presents a set of toolbar buttons (Fig.2) above a largely blank window containing a welcome message. The black area is used for response measurement graphs once these have been made or loaded from saved data.

The Measure button opens a window that allows you to configure and run a frequency response measurement. However, before doing so, you need to set up the computer correctly and, using the preferences window (rightmost button), configure REW's use of your audio interface(s) and then run a sound card calibration. We will look at this in more detail below.

REW features various tools including a signal generator (Fig.3), oscilloscope (Fig.4), and real-time spectrum analyser (RTA) – see Fig.5. These are launched using the toolbar buttons and can be used independently of frequency response measurements. They are useful in their own right for work with circuits, subject to the limitations (discussed last month) that are imposed by using sound cards for measurements.

The signal generator shown in Fig.3 is configured to produce a 1kHz sinewave 0.5dB below the full-scale output level. The tabs in the top part of the window indicate the range of other signal types that can be generated. The signal level can be set using dBu, dBV, volts (RMS) or dBFS units. Calibration is required to set the output voltage accurately (see below).

The "Lock frequency to RTA FFT" box, which is checked in Fig.3, means the frequency is adjusted to the nearest FFT bin centre for the spectrum analyser (RTA), which improves spectral resolution, but restricts the frequencies to specific values based on the FFT. For example, the actual output with the setting shown in Fig.3 will be 999.76Hz, not 1kHz. This is handy when using the spectrum analyser.

The "Add dither" option adds 2 LSB variations in the output signal, which helps to remove quantisation noise from distortion measurements. This is useful for analysing electronics, rather than acoustics, where other noise dominates.

The lock frequency and dither controls just mentioned give some insight into the comprehensive and complex nature of REW. The number of options and settings may seem daunting to new users, particularly if the terminology and related theory are not very familiar. However, REW's documentation is very good, and clearly explains things such as when various options are appropriate to use.

The two input channel Scope tool (Fig.4) provides the basic functionality and controls you would expect from an oscilloscope, including measurement cursors and some maths functions.

The spectrum analyser will show the spectrum of any input signal, but is particularly useful in conjunction with the signal generator. The example in Fig.5 shows a 1kHz (actually 999.7Hz FFT-locked) sinewave.

The harmonics (distortion components) are labelled 2, 3 etc. A distortion analysis is shown at upper left. A peak can be seen at the mains frequency (50Hz); the other parts of the spectrum are noise.

Frequency response in REW

REW makes frequency response measurements using a logarithmically swept sinusoidal signal which, as noted earlier, is faster than a stepped sine approach. The input sweep and response are processed using an FFT and compared to obtain the transfer function and impulse response, from which other measurements, such as distortion, can be derived.

It can also use stepped sines for distortion measurements via the RTA, an approach which is slower but more accurate at lower distortion levels.

REW uses one audio I/O channel for primary measurements (the default is the right stereo channel, as in Fig.1). The other input does not have to be used, but can be looped back (as in Fig.1), where REW can use it as a timing reference to compensate for delays in the sound card and operating system.

The sound card itself may not have a perfectly flat frequency (gain) response,

Getting Started with the B-L475E-IOT01A1

We were contacted by a reader who asked for more detail on configuring the development board used in the article last month.

We did not provide a detailed account of getting started using the SMT32 ecosystem in the articles because there are a number of online resources on this (video and text), one of which we referenced in the June 2025 issue. Typically, these describe 'blinky' projects that flash LEDs.

However, STM32 may be more challenging to get started in than some other systems, like Arduino, so we will provide a few extra notes here.

The configuration of the board should not be a problem because the STM32CubeIDE app does the work for you. You can start a new project for a specific board and all code to configure the MCU to use that board will be automatically written for you. You start with a working project that has no specific function.

One potential problem is that the online examples refer to various boards, so you may have to use a different pin to control the LED, but much of the general content of these examples will be applicable. DigiKey provides a 'blinky' example at **https://pemag.au/link/ac8l**

As is typical, this uses a different board, but the changes needed are minimal. During project creation, search for the board we used (B-L475E-IOT01A1) in the Target Selector, not the one in their example. The main code is in Core → Src → main.c (not just Src → Main) This difference is probably because the example uses an old software version.

The B-L475E-IOT01A1 has two LEDs, so you have a choice of which one to flash. One option is to click the PA5 pin in the CubeMX view and select GPIO_Output (the default is SPI clock) and save the .ioc file.

Alternatively, use LED2, which is configured for use by default on the B-L475E-IOT01A1. You don't need to save the .ioc file ("Save" will be greyed out unless you change something, but it is not needed in here). Use "HAL_GPIO_TogglePin(GPIOB, GPIO_PIN_14);" to toggle the LED instead of the code in the example.

When looking at the autogenerated main code, you will see there are more peripheral initialisation calls, as the B-L475E-IOT01A1 board has more features. After that, create new projects in the same way (with the default configuration), then follow the configuration changes described in the articles. No changes to the board hardware are required.

but REW can compensate for this using a measurement made with a direct connection between the input and output. This could also be used to compensate for the frequency response of any conditioning circuits, which should also ideally have a flat response.

Setting it up

REW obviously needs control of your sound card, so it is best not to have any other audio/media programs running, or have any media playing in a browser when you start REW or one of its tools. On the other hand, you can play media on the PC and observe the audio waveform on the REW scope via a loop-back connection or your device under test.

To get the best results, the REW instructions recommend not simultaneously running any other apps or processes with high processor demand, disconnecting from the internet and switching off wireless networking (to reduce interference).

I tried a few quick experiments while running a real-time spectral analysis and observed significant (temporary) disruption to the measurement when switching Bluetooth on and off and launching a demanding program. If this occurred during a frequency response measurement, it would likely invalidate it.

Therefore, it makes sense to keep the PC doing as little additional activity as possible when making important measurements.

Sound card drivers (or the operating system) may provide audio processing with the aim of enhancing your music listening or gaming experience or applying processing, such as noise cancellation on inputs. These features need to be switched off while making measurements.

For example, in Windows settings (System → Sound → Properties), for the selected output device (eg, Speakers/Line Out), there may be options such as "Audio Enhancements" or "Spatial Sound" under "Advanced Settings", which need to be deselected. You probably also need to set the "Allow applications to take exclusive control of this device" option selected in the Windows audio properties for the device.

The sound card manufacturer may also provide utilities/apps for interface control and/or sound processing as part of the driver install or as separately installed apps. You may also need to use these make sure that all processing is off and the I/O connector settings are configured correctly (for example, the jack socket is set to be a line input rather than side speaker outputs) and to control settings like sampling rates.

Some audio interfaces will attempt to automatically change their configuration when devices are plugged in (eg, in response to headphone impedances on output connections), so it is a good idea to first plug in the leads you will use for measurement and then check the all the sound settings are correct. If possible, switch off auto-detection before adjusting settings for measurement work.

Sound card preferences

REW can use all the audio I/O interfaces that it detects on the computer, and you need to select the appropriate ones and which channels to use (eg, stereo left or right) for input and loop-back. This is done via the REW Soundcard Preferences window (Edit → Preferences → Soundcard).

You also need to select the driver to use (Java or ASIO) and the sampling rate, which must match the setting in the operating system. There are various other settings in the Soundcard Preferences, and you should read the REW help page on this, which has detailed instructions and advice on how to configure things.

REW supports a range of sampling frequencies depending on the sound card. As discussed in depth in the recent DSP series, the maximum frequency that can be measured is half the sample rate (the Nyquist frequency). The sound card should have an anti-aliasing filter, but is still better to avoid using signals with content above this value during measurements.

The instructions recommend using 44.1kHz or 48kHz for acoustic measurements, assuming a 20kHz upper frequency requirement, as higher rates do not improve the results. Higher sampling rates are more demanding (memory and processing), but are required for results at higher frequencies.

Signal levels and calibration

As mentioned above, the sound card will have a maximum input voltage it can handle without clipping – this is the full-scale (FS) value of its ADC. Full-scale would be expected to occur at an equal magnitude for positive and negative excursions of the AC signal. The specific full-scale voltage will vary for different sound cards, but will typically be in the order of a volt for line inputs.

As discussed last month, clipping must be avoided when making frequency response measurements. It can occur in the external circuitry or the sound card. Clipping in the sound card will be detected by REW, and notification can be

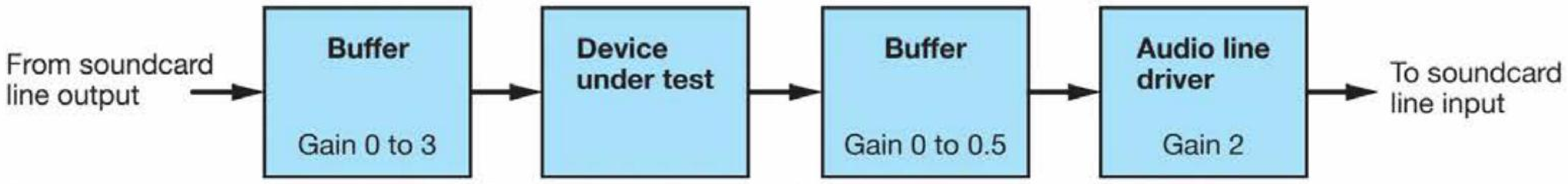


Fig.6: a block diagram of my signal conditioning circuitry for testing the DSP filter.

provided to the user. Measurements can be automatically stopped if clipping occurs.

REW will not detect clipping in the device under test or signal conditioning circuits if the sound card input does not reach full-scale, so care must be taken to avoid this. The signal generator and scope tools can be used before a frequency response measurement to check for clipping or other problems in the circuitry.

The output of the sound card will also have a full-scale output voltage, which will depend on the output volume control setting and possibly other settings.

We can calibrate the signal generator and input so that the numerical values of voltages set and measured by REW are accurate. After calibration, REW will display the full-scale output voltage in the signal generator window (Fig.3) and full-scale input voltage in the RTA window (Fig.4).

The full-scale input voltage is also shown in the scope channel setup dialog, via clicking the leftmost of the three cog icons, near the "CH1-CH2" button – see Fig.4.

To calibrate REW, you need a DMM, audio millivoltmeter or oscilloscope capable of measuring AC RMS voltages at around the 1V level. A basic meter that's accurate at mains frequencies is sufficient.

I/O voltage calibration

After dealing with the operating system settings and REW preferences, proceed as follows.

1) Connect the sound card line input directly to the line output (loop-back in both channels) with a connection that allows you to measure the signal voltage between the ground and signal lines of the output.

I used two audio cables with one connector cut off and the signal and ground (shield) wires soldered to male jumper wires which could easily be plugged into a solderless breadboard or pin headers, but you could also use a splitter cable and clip the meter to a jack plug or other connector.

2) Set the volume control to an output to a low level using the operating system control. Set the stereo balance to centre.

The input (recording) volume in the operating system can probably be set at maximum, but it may depend on the specific setup. If the interface input has a physical gain control (more likely with an external USB unit), this may also need adjusting as part of the process.

4) Run the signal generator, scope and RTA tools in REW, with the signal generator producing a sinewave on both channels (L+R) at a frequency the meter can accurately measure. Fig.3 shows the signal generator configured for a 1kHz sinewave, which was fine for the true RMS meter I was using, but other frequencies can be used.

5) Set up the scope to show both channels (Right and Left) with the voltage scale set so that the full-scale lines are visible. The scope display in Fig.4 shows the input (blue) and output (yellow) waveforms and the full-scale levels (dotted horizontal lines) with signal levels just below full-scale.

6) Set the generator signal level to 0.00dBFS and adjust the system output/main volume until the signal amplitude on the scope is just below clipping. That is, if you increase the volume just above this value, you will see the clipped waveforms on the scope.

The volume control may not provide very fine steps, so it may not be possible to set the output exactly equal to the full-scale input – use the highest value with no clipping.

Measure the signal level with the meter and enter this as a calibration level in the signal generator and RTA via their "Calibrate level" buttons (see Figs.3 & 5). The signal does not have to be at full-scale when doing this – REW will calculate the full-scale values from the current output level setting and input level of the sound card's ADC.

If you change the output level in the signal generator, the meter reading should change to match the new setting, and the RTA and scope should show this accurately. You can switch the generator output level units and RTA y-axis to volts to make it easier to check this.

Once the full-scale calibration is complete, do not change any of the computer or audio interface volume or gain settings.

Conditioning circuit design

Fig.6 shows a block diagram of the circuitry used for the DSP filter frequency response measurement. Of course, this can also be used directly for other circuits under test or adjusted to match different voltage range requirements.

The circuit was designed to provide unity gain from input to output in the audio range, with the possibility to make gain adjustments to fine-tune the signal levels. It was constructed on a solderless breadboard to facilitate experimentation and development. There isn't enough space to cover all the details of the circuit in this article, so we will just provide an overview here.

The first buffer AC-couples the output from the sound card, provides a variable gain of up to three times (adjusted with a trimmer potentiometer), and has high-frequency roll-off (at around 250kHz) to help remove any RF signals that might be picked up at the input.

With the sound card I was using, the maximum (just below full-scale) output from the sound card was 0.431V RMS, which is 1.22V peak-to-peak for a sinewave. The same value applies to a unity-gain circuit. For testing the DSP filter, the signal needs to be amplified to around 3.2V peak-to-peak (just under the microcontroller's ADC's 3.3V input range), which is 1.13V RMS.

A gain of 2.6 times (3.2 ÷ 1.22) is required, hence the buffer's maximum gain of 3 times.

As described in the DSP series (August & September 2025 issues), the MCU digital filter implementation includes a protection circuit, AC-coupling and DC shift to bias the input to 1.65V (half the 3.3V supply). This is included in the DUT block in Fig.6, along with a reconstruction filter at the MCU DAC's output (Fig.7).

No anti-aliasing filter was used at the MCU's ADC input because the frequency response test would not be applying signals with content beyond the Nyquist limit.

The reconstruction filter used was a fourth-order low-pass op amp based circuit with a 20kHz cutoff, not the simple RC filter from the previous basic test

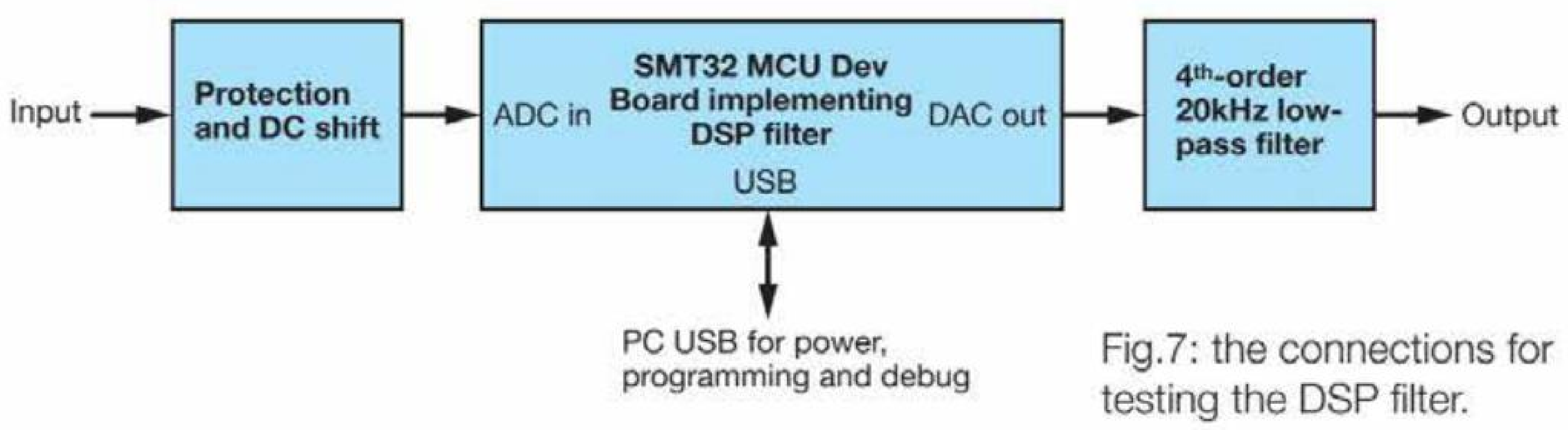

Input
Protection and DC shift
ADC in
SMT32 MCU Dev Board implementing DSP filter
DAC out
USB
4th-order 20kHz low-pass filter
Output
PC USB for power, programming and debug

Fig.7: the connections for testing the DSP filter.

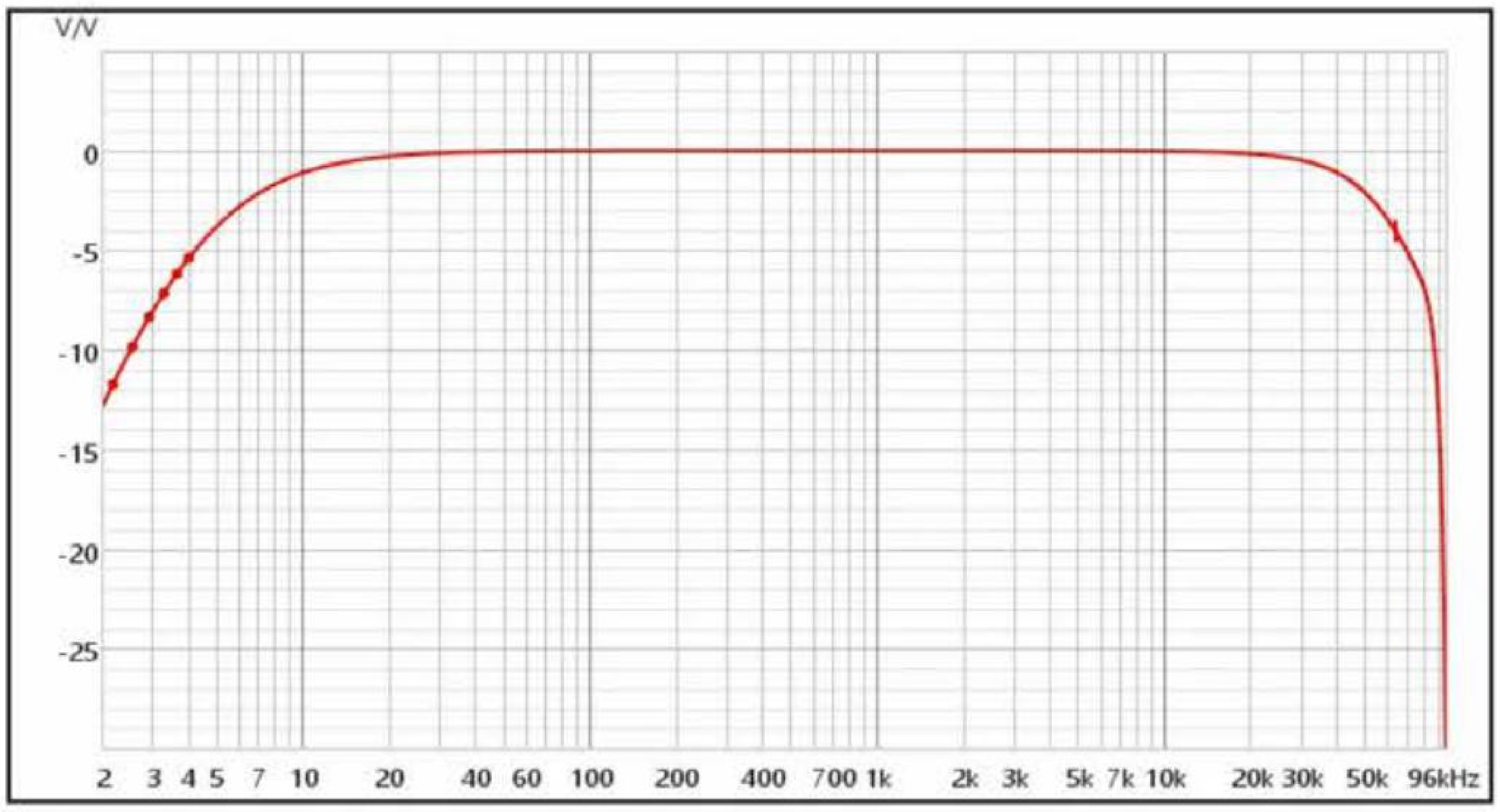


Fig.8: REW's calibration measurement for my sound card (16 bits, 192kHz sampling rate).

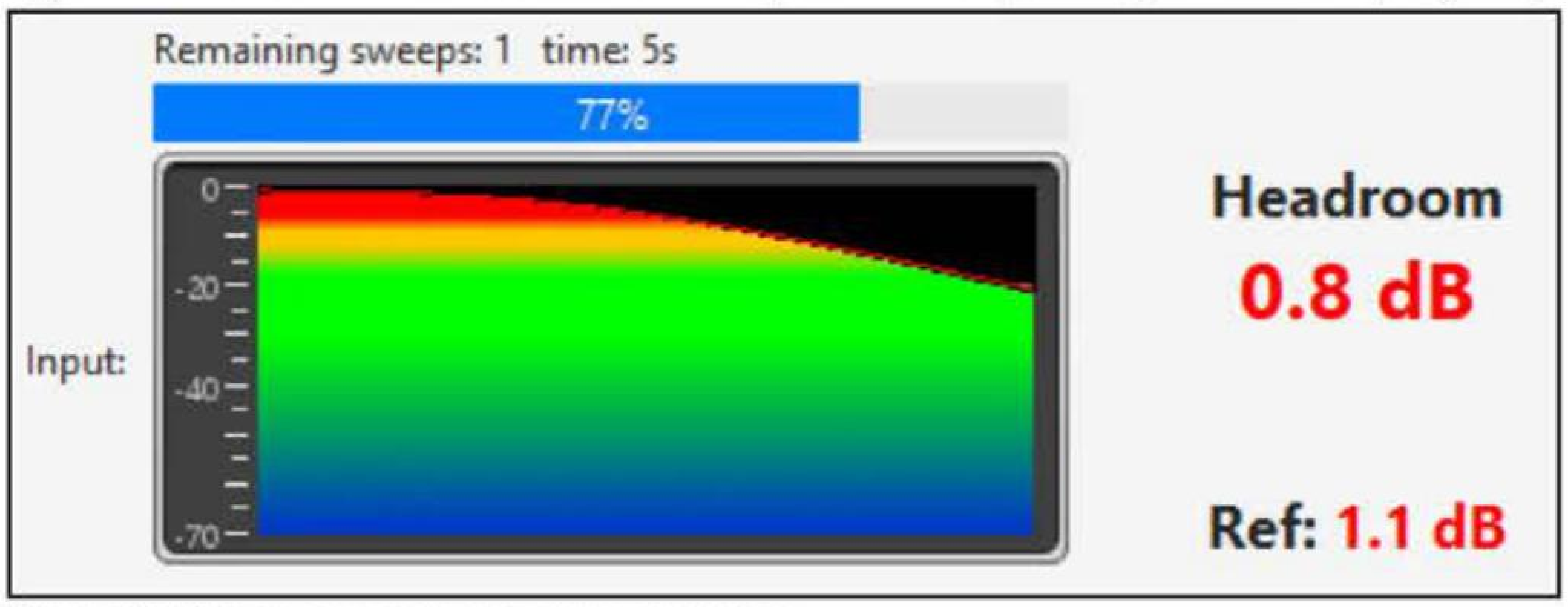


Fig.9: REW's measurement progress display.

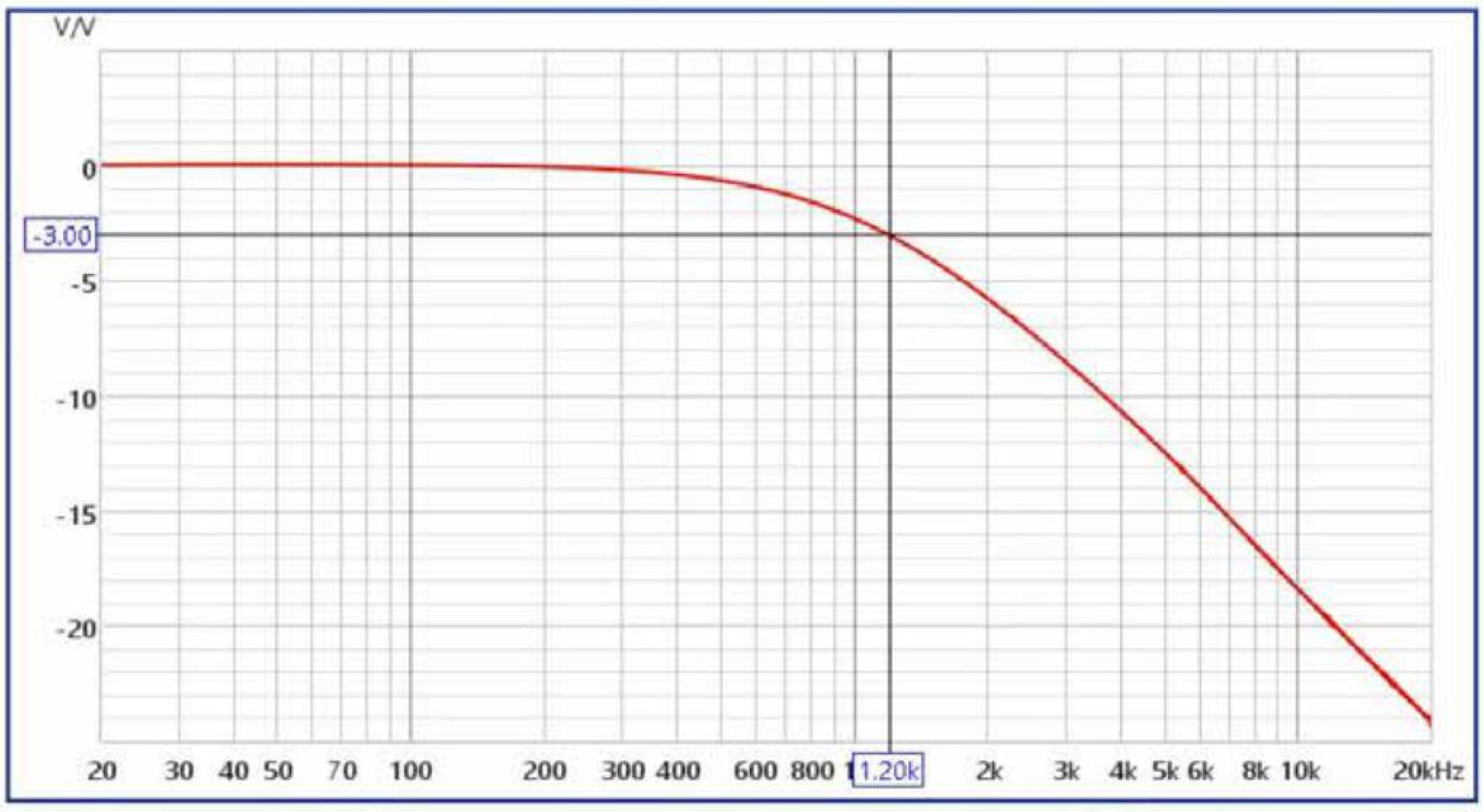


Fig.10: a plot of an RC low-pass filter response measured using REW.

(September 2025). This means the reconstruction filter gain is flat throughout most of the stop-band up to the near DSP filter's Nyquist limit of 24kHz.

The RC filter was fine for quickly checking with an oscilloscope that the cutoff of the DSP filter looked about right, but would have had a significant effect on the overall frequency response if used in this measurement.

The DSP filter and reconstruction filter have unity gain in the passband, so the output of 3.2V peak-to-peak needs attenuating back to 1.22V peak-to-peak for overall unity gain and to suit the sound card's maximum input level.

The output from the device under test goes to a second variable gain buffer and then to an audio line driver. The audio line driver is more capable of driving capacitive loads and long cables than a typical op amp, and can drive both single-ended and balanced inputs.

The line driver has a gain of about two times, which needs to be taken into account in the attenuation provided by the buffer. A gain of about 0.19 is required (1.22 ÷ 3.2 ÷ 2).

Sound card calibration

REW can measure the frequency response of a sound card and use this to compensate for any variations in sound card gain when making measurements. This is done via the "Calibrate sound card" button in the Preferences window. There are step-by-step instructions provided after you click the button and further details on the "Getting set up for measuring" help page.

It is suggested that REW output volume and sweep level settings (in Preferences) of 0.5 and -12dB to -6dB are used, respectively, but this is aimed at acoustic measurement. I tried various options, checking the frequency response and distortion graphs, and got good results with settings of 1.0 and -1.0dB, respectively.

An example sound card calibration measurement is shown in Fig.8. A key aspect is that it is flat over the 20Hz to 20kHz range.

After calibration, you need to save the results to a calibration (.cal) file via the "Make a cal file..." button in the preferences window (you are reminded to do this). You can have as many of these calibration files as you want, selecting the relevant one when you make a measurement. The calibration also appears like a regular measurement, with various graphs available to view.

The frequency response (as in Fig.8) is referred to as "SPL and phase" in the set of buttons for selecting which graphs to view, and is displayed by default. SPL is sound pressure level and reflects REW's primary use. REW also uses microphone calibration files, which relate to SPL meters, so are not needed for electronic circuit measurements.

Any measurements, including those used for calibration, can be saved to a file and opened again in REW later. This is a different file type (.mdat) for the calibration file. Measurements are saved separately, via the list of measurements in the main REW window.

Making measurements

Measurements are made via the "Make a measurement" window after clicking the Measure toolbar button. There are a lot of settings and options, but the documentation explains these in detail, so we just give a brief outline here.

The measurement type needs to be SPL for a frequency response. You can give the measurement a name and type in notes if you want.

Key things to set are the frequency range and the output level. A level of 0dBFS should be OK with a unity-gain circuit without resonant peaks, but a slightly lower level may give better distortion performance. There is an option to abort the measurement if clipping occurs, which should usually be left on.

There is a setting for sweep length (the number of sample points). Longer sweeps provide better signal-to-noise ratios in measurements and are suited to use with electronics (the help advises against their use with loudspeakers). The longest option (4M points) was

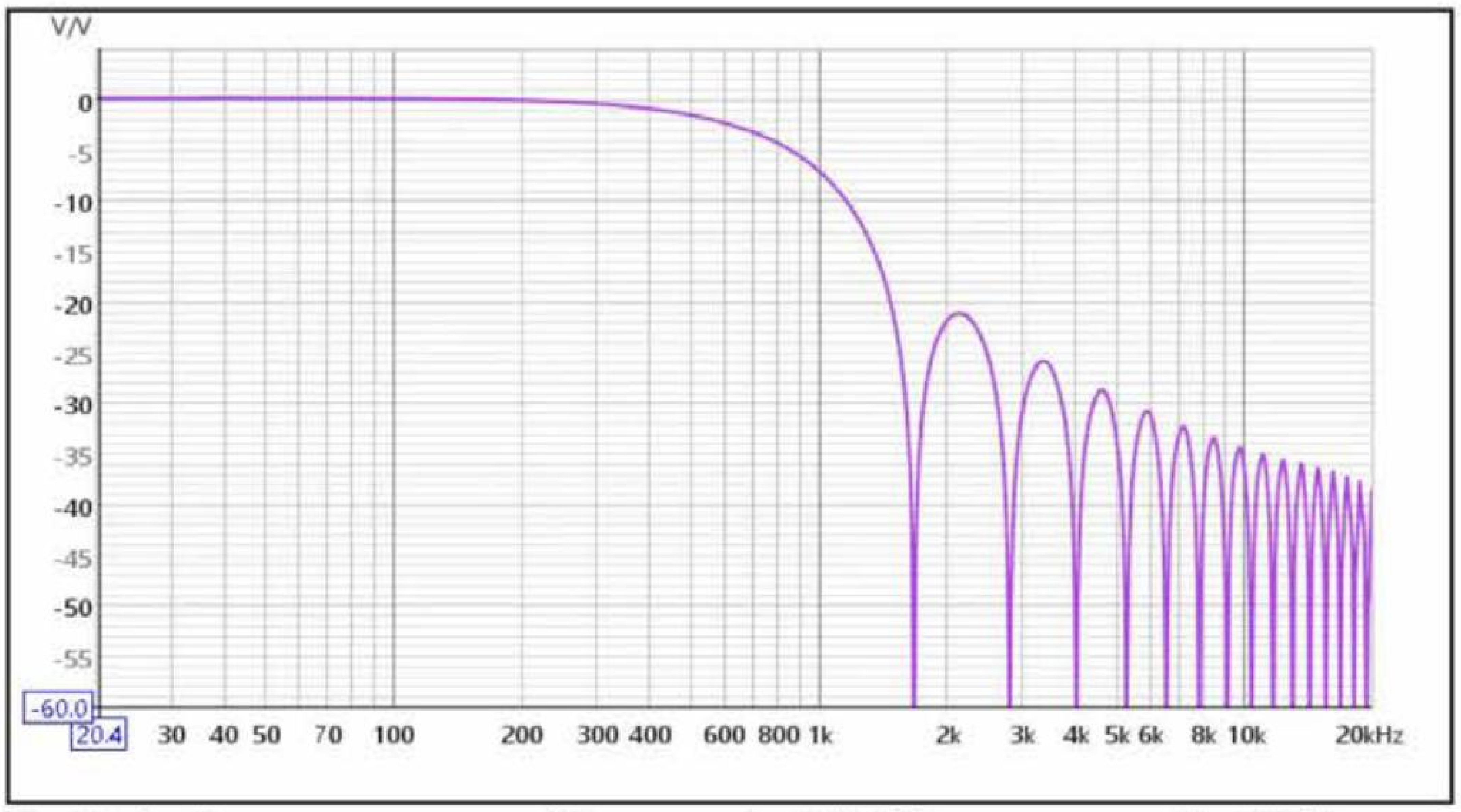


Fig.11: the frequency response of the example digital filter as measured by REW.

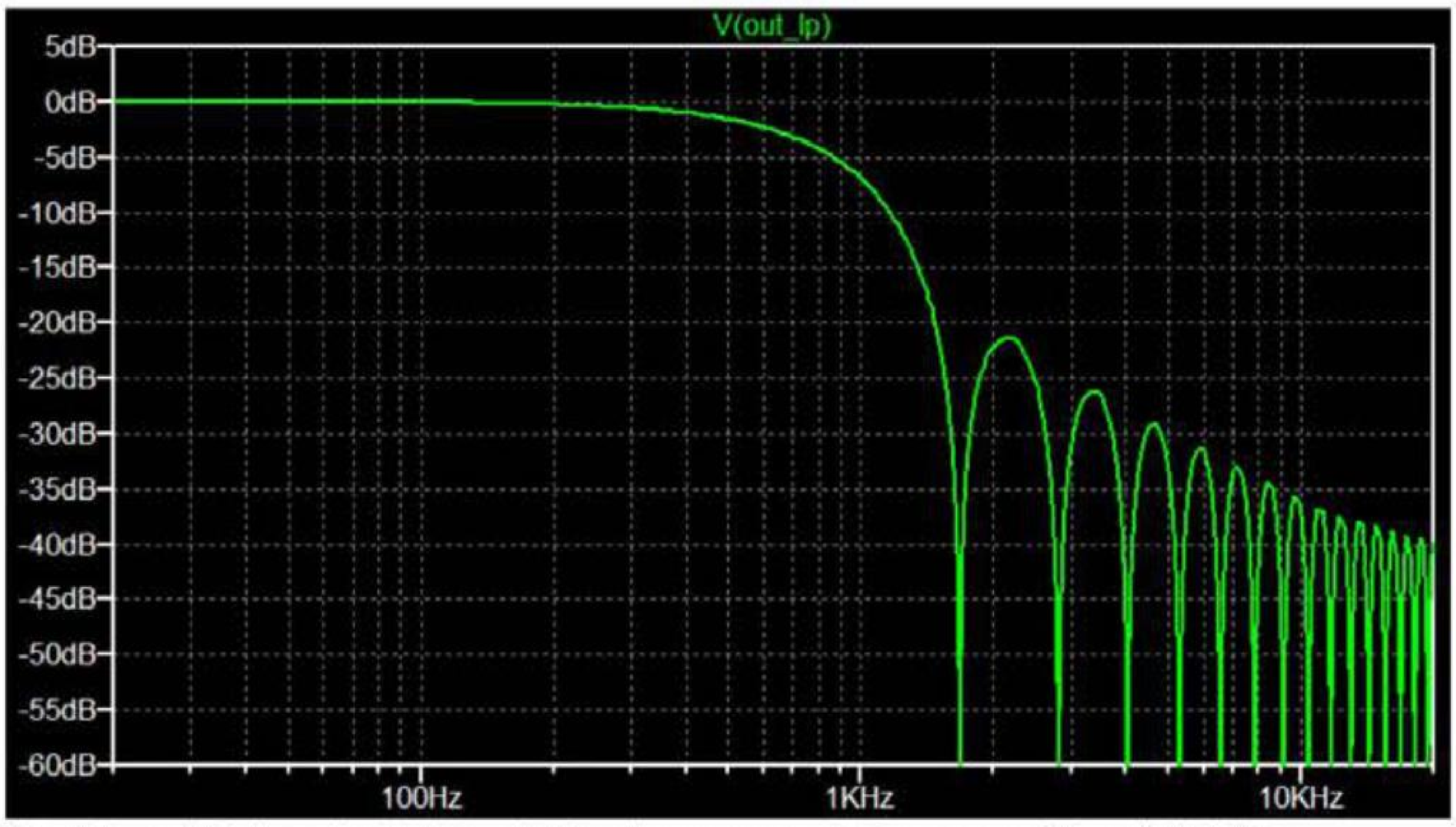


Fig.12: an LTspice simulation plotting the expected response of the digital filter.

used for the measurements here. You can also run multiple sweeps and average the results.

You can set some sound card options, but these should already be as required as they are based on the Preferences settings. You can select the calibration file to use, with the default being the last one created.

Once you are happy with the settings, click the Start button to make the measurement. REW will show the measurement progress via a small rolling graph of the measurement and information on the remaining number of sweeps and time (Fig.9). It also shows the headroom in decibels below full-scale for the largest reading so far.

After the measurement, REW may give a warning if the levels were excessively low, if clipping was detected, or high levels of distortion were present.

Measurement results

Before attempting to measure the DSP filter, I tried a simple RC low-pass circuit as the device under test (as in Fig.6). This used a 330nF capacitor and a 390Ω resistor. The cutoff (-3dB) frequency for this circuit is 1.24kHz; $1 \div 2\pi RC = 1 \div (2 \cdot \pi \cdot 390\Omega \cdot 330\text{F} \cdot 10^{-9})$. Using measured values of the components (347nF and 386Ω), a cutoff of 1.19kHz would be expected. The results are shown in Fig.10. Using the cursors available on the results graph in REW, the cutoff was 1.20kHz, which is within 1% of the expected value.

I moved on to measuring the digital filter using the circuits shown in Figs.6 & 7. The filter configuration was a 1kHz low-pass windowed sinc, with 37 coefficients, a 48kHz sampling rate, and a rectangular window running on the B-L475E-IOT01A1 STM32 development board, as described in recent articles.

The results are shown in Fig.11. Fig.12 shows an LTspice simulation of the same filter using the approach described in detail earlier in the DSP series. Comparison of the two graphs shows a good match, and confirms that the filter implementation is working correctly, and that REW is a useful tool for making such measurements.

Coming up

Next month, we will continue to explore this topic, focusing on the signal conditioning circuitry. PE

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Drive
- up to 256 microsteps
- 50 V / 6 A
- USB configuration
- Isolated
- up to 32 microsteps
- 30 V / 2.5 A
PoScope Mega1+
PoScope Mega50
Measure
- up to 50MS/s
- resolution up to 12bit
- Lowest power consumption
- Smallest and lightest
- 7 in 1: Oscilloscope, FFT, X/Y, Recorder, Logic Analyzer, Protocol decoder, Signal generator

Net Work

Alan Winstanley

Some grim realities behind Britain's troubled energy market are revealed. Also, eBay is trying to re-invent itself – will it succeed? I will also suggest some handy test meters and low-cost gadgets from China.

Regular readers might recall my mini-series entitled "From Pipelines to Pylons" (*Everyday Practical Electronics*, August & September 1999), which told the story of Britain's electricity generation and distribution network. National Power generously allowed me to wander around a nearly new power station during its annual shutdown, when the plant's inner workings were laid bare.

The site, located near Killingholme on Britain's east coast, was built as an 'off-the-shelf' generator during the 1990s, in a period known as the "dash for gas". Combined cycle gas turbine (CCGT) power plants were popping up almost everywhere, fuelled by plentiful supplies of cheap natural gas piped in from the North Sea.

It was fascinating stuff for someone more used to working with milliamperes rather than megavolts. The generation process started with a gas pipeline that fuelled the 650MW power plant. The heat recovered from three gas turbines then drove a fourth steam turbine to improve the plant's efficiency and cost effectiveness, helping it to compete in an open energy market.

Ed Miliband (a one-man band?) sings the praises of wind farms and renewable energy. Source: Instagram, 2023.
The answer my friend, is blowin' in the wind.

I then saw how power plants like Killingholme (**https://w.wiki/FDhm**) would bid a price in pounds per megawatt-hour for the day's output, so the National Grid could choose what mix of generators (coal, gas, nuclear and hydro) and interconnectors (importing electricity from abroad) would be utilised that day.

More than anything, gas was plentiful and cheap at this time. But Killingholme's ownership would pass through several hands until the plant was ultimately deemed no longer financially viable.

Britain's current energy plight is perhaps perfectly captured in the YouTube video of Killingholme A being demolished (**https://youtu.be/3k8SjEqVf0Q**). It's a policy that saddens me to this day and is a topic that I discuss in more depth next.

Blowing in the wind?

Britain's energy policies are now diversifying away from fossil fuels, towards renewable 'green' energy instead. Becoming self-sufficient in energy is something that the UK has never achieved in 50 years, after the country lost both the will and the expertise to build more nuclear power stations.

Doubtless, the Windscale (UK), Three Mile Island (USA), Chernobyl (Soviet Union) and Fukushima (Japan) nuclear calamities tarnished the reputation of the nuclear power industry.

In the 1970s, newly discovered North Sea 'natural gas' helped Britain to wean itself off manufactured 'town gas' (coal gas). Current energy policies and economics are seeing to it that oil and gas operations are gradually winding down in pursuit of a fossil-free renewable future.

Even so, the UK faces all sorts of uncertainties, including conflicts, geopolitics and infrastructure bottlenecks, that are brushed aside by the political classes.

Debates are raging about the wisdom of shutting off our natural gas resources when they could feasibly be called on to plug the country's energy deficit.

A publicly owned company based in Aberdeen, Great British Energy (**www.gbe.gov.uk**), was established to deliver these new sources of renewable energy. A change of government has seen Mr Ed Miliband installed as Secretary of State for "Energy Security and Net Zero".

Consequently, the British government is dogmatically pursuing a supposedly 'low-carbon' Net Zero policy of building wind and solar farms at all cost (literally). More about that in a moment.

In recent years, I've described the developments in small modular reactors (SMRs), which are downsized nuclear power stations intended to boost our base-load capacity. SMRs that can be built onsite have been on the cards for some years, but it would take about a decade before any of them finally came online.

A two-year long 'competition' was held to find a preferred bidder for Britain's SMR program. As I described in earlier columns, several contenders, including NuScale and GE-Hitachi, dropped out along the way. In June this year, perhaps unsurprisingly, Rolls-Royce was crowned as the competition winner to design and build SMRs for the British market, which is welcome news.

Nuclear power will possibly be the only viable long-term solution for decades to come. Still, the first SMRs won't go live until about 2030, when Sizewell C is also scheduled to start production. While Killingholme's CCGT plant lasted just 20 years, Rolls-Royce promises a 60-year lifespan for its SMRs.

ROLLS
ROYCE
SMR

Rolls-Royce has won the UK competition to design and build the next generation of small modular reactors, housed in futuristic buildings.

A vision of fusion

In the very distant future, nuclear fusion may provide the ultimate answer to our energy woes. The Joint European Torus (JET) was built in Britain as a pilot plant to explore the viability of building a commercial fusion power plant.

The highest temperatures ever seen in the universe have since been artificially created and recorded, and in late 2024, JET gained the world record for the highest energy output ever seen, just before the 40-year-old device was retired for good. There's more information on the JET at **https://ccfe.ukaea.uk/programmes/joint-european-torus/**

Extreme challenges in harnessing plasma must be overcome before any tokamaks (a nuclear fusion toroid – see *Net Work*, December 2022) will ever see regular service. The International Atomic Energy Authority says that more than 130 experimental public and private tokamaks are either operating or planned around the world.

Work at the multinational International Thermonuclear Experimental Reactor (ITER) tokamak, a large-scale nuclear fusion pilot plant based in France, has been dogged by lengthy delays. I explained more about ITER in the November 2022 issue, and there's more background at **www.iter.org**

Energy security has improved little since the invasion of Ukraine disrupted the wholesale gas market, which in turn drove electricity costs upwards, where they have stayed ever since.

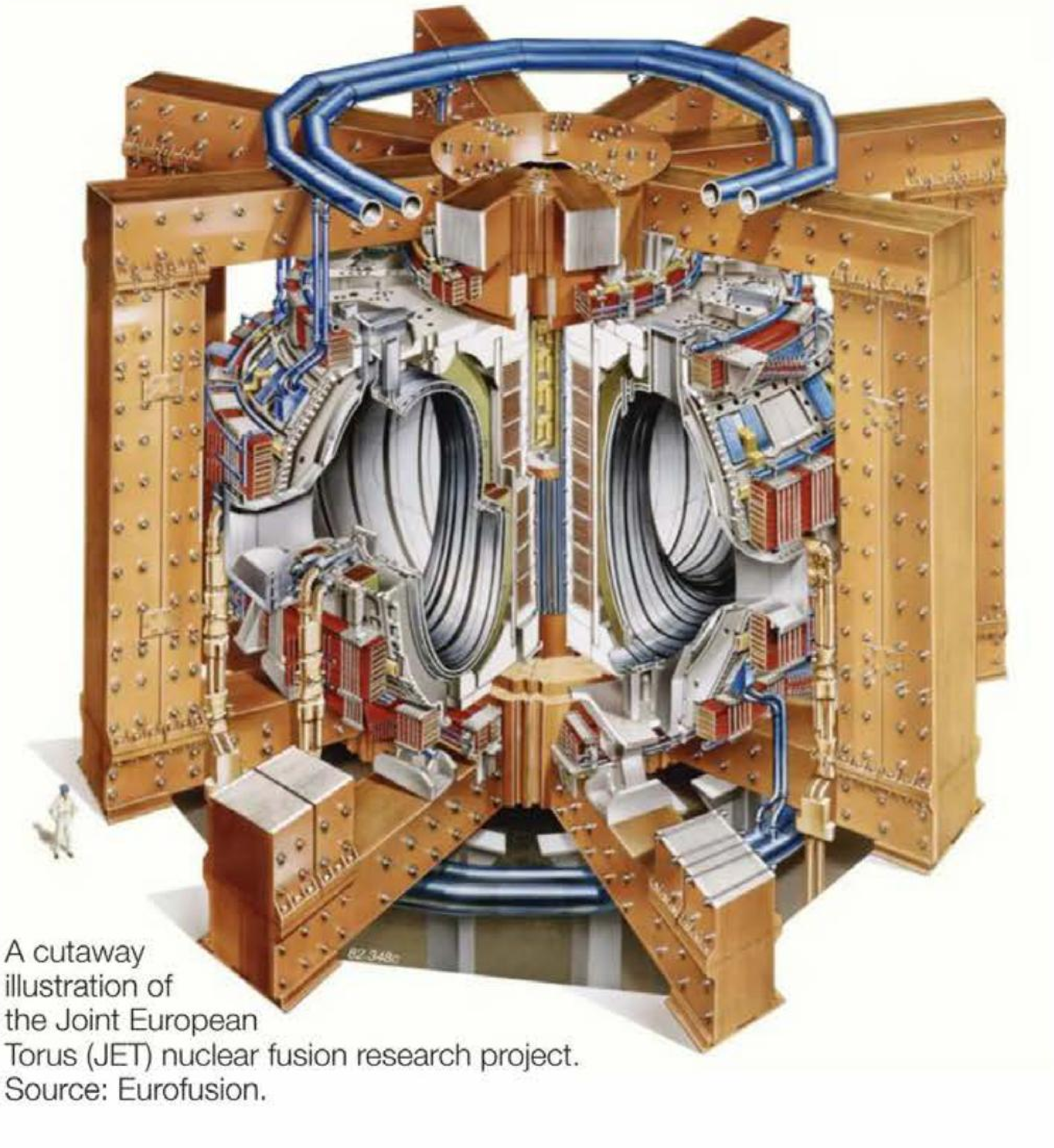
Britain's gas storage resources, such as the giant undersea Rough gas cavern operated by Centrica, are intended to hold a few days' buffer supply of gas, but these too have been imperilled due to the huge investment now needed and the lack of government support.

Time will tell whether the lights will stay on, or whether we will have a white-knuckle ride instead as Britain heads into winter, when demand will undoubtedly soar.

Sunny side up

Many of us, especially in the provinces or rural areas, are decrying the impact of new 'solar farms', with agricultural land being carpeted with Chinese-made solar photovoltaic (PV) arrays.

On some planning applications that I viewed, what I thought looked like hundreds of acres of lavender or borage (starflower) crops were in fact solar panels. The agricultural



A cutaway illustration of the Joint European Torus (JET) nuclear fusion research project. Source: Eurofusion.

land would be decommissioned forever, being of no use for anything else – not even for livestock.

Much has been written about the viability of wind farms. Ed Miliband is devoted to the idea, and ever-larger wind turbines, rated 15MW or more, are being developed. How to recycle gargantuan fibreglass turbine blades at the end of life is a concern. These things are populating vast tracts of countryside, as well as inhospitable areas including the North Sea.

The world's largest offshore wind farm, Dogger Bank, between England and Denmark, has announced a fourth phase (Dogger Bank 'D') that will add another 113 wind turbines to generate a further 1.5GW of electricity. GE Haliade-X wind turbines (see *Net Work*, January 2020) are used, which are made in Britain, France and Japan.

The current United States administration has taken the opposite view about the viability of wind farms. In August, it stunned the market by cancelling $679 million worth of funding for a dozen offshore wind farm projects.

One catastrophic knock-on effect of this loss is the heavy damage inflicted on Denmark's Ørsted, which is the world's largest developer of wind farms, leaving Ørsted reeling to re-finance itself. Ørsted has terminated work on the Hornsea 4 offshore wind farm, blaming spiralling supply chain costs and interest rates.

A fundamental problem with wind and solar renewables is that neither can generate power all the time. Sprawling battery storage units are springing up, manufactured by Tesla and others, that aim to iron out some of the wrinkles in electricity supplies caused when wind and solar renewables are dormant.

Trials of vehicle-to-house (V2H) charging are continuing. The idea is that an EV battery can be plugged into a special charger that either draws power from or feeds power into the national grid, effectively selling its own electricity back to it. There are more details on V2H at **www.indra.co.uk/v2h**

Incidentally, Tesla has applied to the UK energy regulator Ofgem for a licence to enter the British market as an electricity supplier in its own right, competing against all the well-known names.

The unspoken truth about our energy policies

Politicians, activists and other vested interests have long fed pliant British consumers a green diet that praises the merits of renewable energy and the need to reduce or capture 'carbon' (meaning the gas carbon dioxide, not the solid). Consequently, consumers continue to pay through the nose for energy.

A prototype of GE Renewable Energy's Haliade-X wind turbine, now being used in the world's largest offshore wind farm at Dogger Bank in the North Sea.

There's a wholly different side to the story, though. One industry expert whose work I respect deeply is Kathryn Porter, an independent consultant working in the energy markets.

Ms Porter has published several very insightful reports that shine a light on the true state of Britain's broken energy market. I know that some *Net Work* readers have worked in the energy sector themselves and follow keenly the current trends in electricity generation, so I can strongly recommend Kathryn Porter's report entitled *The true affordability of net zero.*

The report explicitly outlines everything that is wrong with Britain's current energy policies. One key point is that wind farm operators are often paid not to produce electricity. As Ms. Porter states:

Energy Secretary Ed Miliband claims that renewables are cheap and will lead to lower bills. This sounds great, but unfortunately is not true. The only renewables that are viable at scale in the UK are wind and solar, which are intermittent – that is, they do not work all the time.

Wind turbines do not generate when it's not windy, and solar generates nothing at night. This includes the peak demand periods, which occur at dinnertime in the winter, which is after sunset. On average, only 35% of the possible amount of electricity that could be generated actually is.

Although the national grid was devised to be resilient and transport electricity anywhere in the country, Ms. Porter explains:

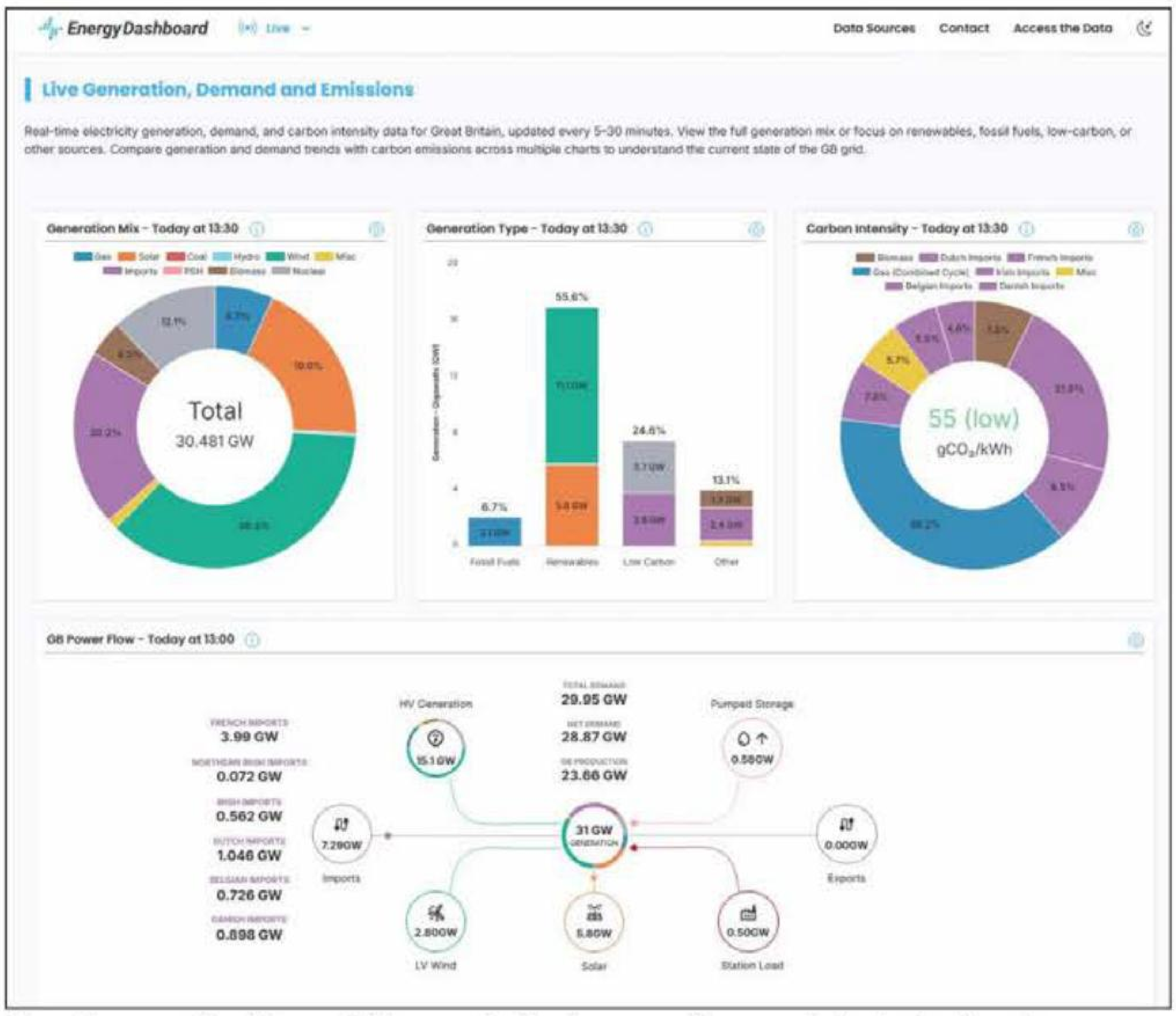
… the construction of this grid infrastructure has failed to keep pace with need, resulting in grid congestion and constraints. Constraints mean generation on one side of a grid bottleneck has to be turned down, and other generation downstream of the bottleneck turned up, in order to serve consumers.

Because renewables subsidies are only paid when a generator [supplier] is running, being constrained or curtailed off would mean the loss of subsidy payments, so the generator [supplier] receives a compensating payment known as a 'constraint or curtailment payment'.

In this case, the consumer pays the downstream generator – typically a gas power station – for producing the electricity [that the consumer] actually uses, plus a constraint payment to the windfarm whose electricity was not used. These constraint fees amount to £ billions per year and are added directly to consumer bills.

… when supplies are deliberately 'constrained', consumers must pay [for both] a gas power station to generate the electricity they actually use, and also pay windfarms not to generate the same amount of electricity. Consumers pay twice because investments in the power grid have failed to keep pace with the construction of subsidized windfarms.

The idea that rising bills are due to "international gas prices going up" is rubbished by Ms Porter; she points out that wholesale prices are stable if not falling, but retail prices are loaded with all sorts of hidden costs. Foreign countries also have



EnergyDashboard
Live
Data Sources
Contact
Access the Data
Live Generation, Demand and Emissions

Real-time electricity generation, demand, and carbon intensity data for Great Britain, updated every 5–30 minutes. View the full generation mix or focus on renewables, fossil fuels, low-carbon, or other sources. Compare generation and demand trends with carbon emissions across multiple charts to understand the current state of the GB grid.

Generation Mix – Today at 13:30
Gas
Solar
Coal
Hydro
Wind
Misc
Imports
PSH
Biomass
Nuclear
Total
30.481 GW
Generation Type – Today at 13:30
55.6%
24.6%
13.1%
6.7%
Fossil Fuels
Renewables
Low Carbon
Other
Carbon Intensity – Today at 13:30
Biomass
Dutch Imports
French Imports
Gas (Combined Cycle)
Irish Imports
Misc
Belgian Imports
Danish Imports
55 (low)
gCO₂/kWh
GB Power Flow – Today at 13:00
HV Generation
15.1 GW
TOTAL DEMAND
29.95 GW
NET DEMAND
28.87 GW
GB PRODUCTION
23.66 GW
Pumped Storage
0.58GW
FRENCH IMPORTS
3.99 GW
NORTHERN IRISH IMPORTS
0.072 GW
IRISH IMPORTS
0.562 GW
DUTCH IMPORTS
1.046 GW
BELGIAN IMPORTS
0.726 GW
DANISH IMPORTS
0.898 GW
7.29GW
Imports
31 GW
GENERATION
0.00GW
Exports
2.80GW
LV Wind
5.8GW
Solar
0.50GW
Station Load

The Energy Dashboard Live website is one of several that display the power consumption and distribution of Britain's electricity network.

to buy gas on the same international markets but have fewer energy levies, so they see no such increases in domestic bills.

Due to the imminent Ofgem price cap increase (see **https://pemag.au/link/ac8c**), consumer bills are set to rise by a further 2% this year. Ms Porter summed it up in a recent Telegraph article: "Gas is explicitly not the reason for the latest increase in the price cap – government policy is."

The risks faced by our energy networks this coming winter could get worse still. The UK imports and exports electricity through a network of undersea 'interconnects'. As I write this piece, Kathryn Porter has reported in the Telegraph that Norway, a country heavily reliant on hydroelectricity, is suffering extreme problems with reservoir water shortages.

This could directly affect the country's ability to generate hydroelectricity during winter, which may result in rationing and impact Norway's electricity exports through the interconnects to Scandinavia, mainland Europe and the UK.

You can download *The true affordability of net zero* from **https://pemag.au/link/ac8d** and read more about the brilliant work of Kathryn Porter at the Watt-Logic website, **https://watt-logic.com**

Meanwhile, the website at **www.energydashboard.co.uk/live** lets us keep an eye on things by displaying the UK's energy consumption and demand data in real time (an icon in the upper-right corner toggles dark or light web page views).

Going postal

In September's *Net Work* I reported that eBay was eliminating private seller fees; buyers would pay a so-called "Buyer Protection Fee" instead. Clearly, this move was lifted straight out of Vinted's playbook.

Until recently, eBay would also try to seize control of the seller's dispatch and delivery options. Such unwarranted interference could, however, be overridden when items were listed for sale, leaving private sellers free to choose their own courier and timescale instead.

I spoke too soon: eBay is now forcing private sellers to accept eBay's choice of courier, either Royal Mail or Evri (formerly My Hermes). That wouldn't be so bad except that eBay then also guesstimates the weight and size of your parcel, even if it's not yet known, and it levies postage accordingly. This had thrown up all sorts of problems for private sellers.

eBay has given this compulsory regimen the beguiling name of "Simple Delivery", but in many cases it's proving anything but simple and is causing lots of head scratching (and despair!) instead. Numerous private sellers complain in forums about how eBay's new Simple Delivery rates make their sales non-viable (eg, small, cheap items being charged small parcel rates etc).

Sellers also find that items that are automatically relisted for sale have been changed abruptly by eBay, to impose Simple Delivery on them, which sometimes makes an item's sales price unprofitable.

Having grabbed the steering wheel for themselves, eBay has taken to giving fee-paying buyers a running commentary about their delivery, in an effort to cuddle up to them. Good news! Your item's been dispatched! It's on the way! It's arriving soon! Get ready to receive it! It's out for delivery! It's been delivered! Tell us what you think! And so on. (I must admit, Temu is just as bad.)

eBay's policy on Simple Delivery can be viewed at **https://pemag.au/link/ac8e**

A popular e-commerce news website has plenty to say about it at **https://pemag.au/link/ac8f**

Clearly, eBay is striving to remain relevant as an online marketplace. It faces stiff competition from Facebook Marketplace, Amazon, Etsy, Vinted and live-streaming auction sites like **WhatNot.com**

As a sign of how eBay seems to be thrashing around, it then suddenly dropped Buyer Protection Fees from 75p to only 10p per item, plus a percentage.

Disgruntled private sellers are struggling to find workarounds for Simple Delivery. Furthermore, eBay's "Task list" prods sellers into dispatching their item within two days. Private sellers have no choice but to comply with eBay's Simple Delivery and "Tasks", but some forum users say they resent being treated like order pickers and packers.

Others are doggedly re-editing scores of listings to make them viable again, while some sellers are taking items off sale, and others have given up on eBay altogether.

For some folks, the complexity and bossing around by eBay's Simple Delivery is the final straw. Bulk-buying sites such as Vintage Cash Cow and DontSitOnIt are gaining popularity and have none of the hassle.

Incidentally, for UK readers only, at least the Nectar loyalty card scheme is still operating, for now anyway. Over time, Nectar points

The Aneng M109 compact DMM actually speaks when measuring or selecting functions! It includes a non-contact voltage test function.

can accumulate into handy pocket money to spend on eBay, Argos, Esso, Sainsbury's and others (see **https://www.nectar.com/card/spend**). When buying, you must click through to eBay from the Nectar website via **https://www.nectar.com/brands/588765**

If you forget, simply keep items (unpaid) in your eBay shopping cart, click away to Nectar and then return to eBay again through the affiliate link to earn your points. You can set up a Nectar account and link it to eBay at **www.nectar.com**

The best days of eBay and the heady buzz of last-minute 'sniping' in online auctions are now distant memories. It seems to me the online bazaar is trying to re-invent itself as a corporate and consistent-looking (if bland) marketplace, devoid of the personal interaction and fun that many private eBayers used to enjoy. It will be interesting to see what ideas eBay comes up with next.

Trading blows

In September's column, I outlined multiple interesting finds that I'd uncovered on China's Temu website. Like it or loathe the idea, Temu's online operation came out of nowhere in Britain just two years ago, and its functionality is nothing short of sublime. [Editor's note – of course, it wasn't such a revelation for those already using Alibaba, AliExpress or Taobao.]

In the past 18 months, I've received some 50 deliveries of items for the home, garden, workshop and office, with only a very small proportion of items failing to satisfy (refunds are made instantly).

There can be no doubt that Temu's savage 'buy direct from China' strategy is eating into both eBay's and Amazon's businesses. Neither of them can complain since they've had things their own way for nearly 30 years, though.

Temu includes VAT in sale prices, which therefore contributes funds to the UK Exchequer. Items listed as shipped from a "local warehouse" imply that sellers are located in the UK and selling through the Temu platform, a trend that is on the increase. Extra postage rates and/or minimum order values may apply.

Both Temu and other foreign sites such as AliExpress and Banggood rely on the fact that private UK buyers can import orders valued below £135 without attracting import duties. Over that value, duties of 2.5% start to be levied, for which shippers will likely charge an administration fee (known as "brokerage") to cover customs clearance.

America's erratic decision to eliminate the 'de minimis' trade exception and impose tariffs on all imports has resulted in the UK's Royal Mail charging an extra 50p to cover the work when posting to the USA. eBay too has inflicted some problems on sellers who ship to the States, as explained at **https://pemag.au/link/ac8g**

Measured speech

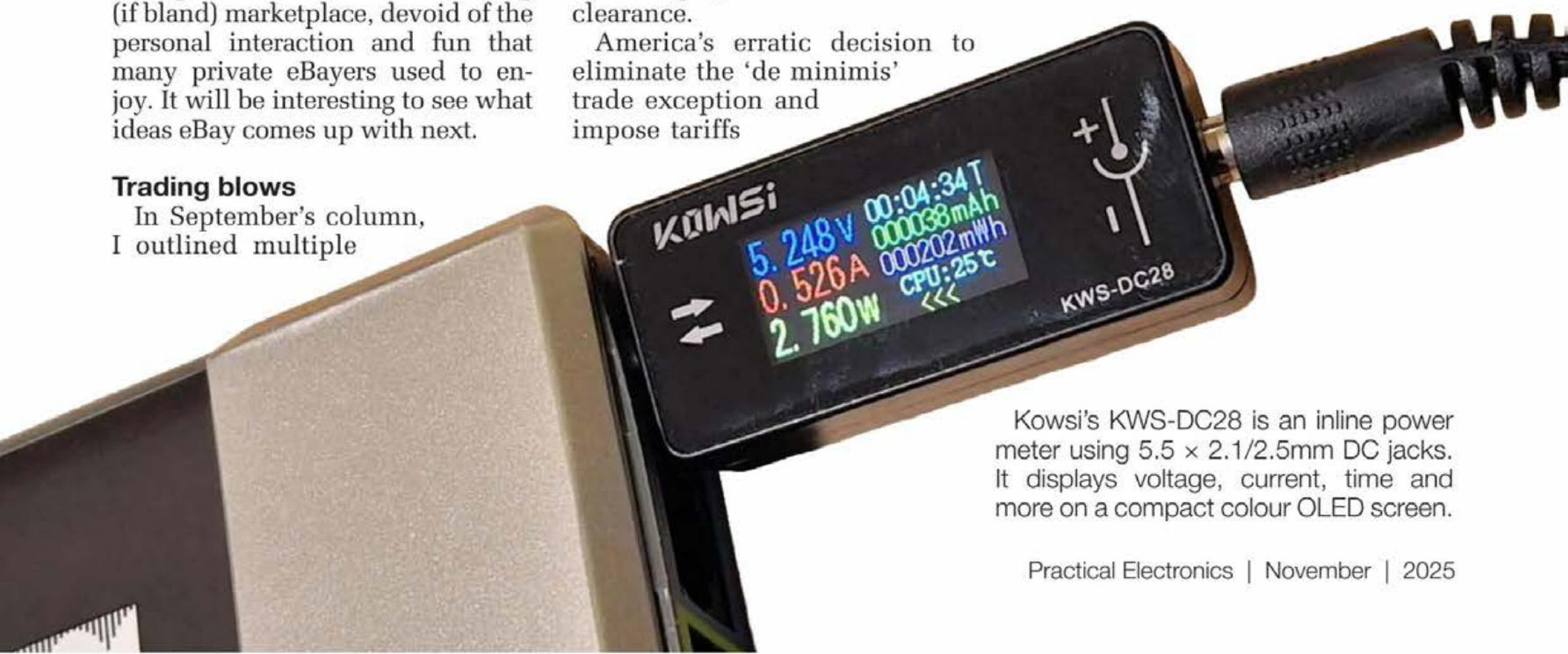
I felt some items listed on Temu might interest the electronics hobbyist. I've now tried an Aneng M109 digital multimeter, a compact DMM that actually talks. The clear-enough speech tells you what meter range has been selected, a feature that I find genuinely useful.

It offers the usual ranges plus capacitance (up to 4μF), 4MHz frequency and non-contact voltage (NCV) mains wiring detection, with a built-in LED illuminating the area. It's listed on eBay at £18.52, but mine arrived from Temu for a mere £4 or so. What's not to like?

I then found a neat little battery and coin cell tester, also made by Aneng. The BT138 comprises two test pads separated by a 100mm ribbon. Each pad contains a magnet, so it's fiddle-free: you simply click it onto the cell or battery under test and read the voltage directly. It uses the test battery as its power source, and it's good for 1.2-4.8V cells, 18650 batteries and more.

A pair of contacts for 9V (LR22/MN1604) batteries on it completes the picture. It was about £2.50 – around ⅓ of eBay's prices.

Back in the July 2024 issue, I highlighted Kowsi-brand USB dongle-style testers with OLED displays that measure current, voltage and other parameters. They're useful when recharging gadgets or smartphones etc. On Temu, I recently found the Kowsi KWS-DC28, which measures 4-30V DC, 0-12A, power consumption in Wh (watt-hours) and more data besides.



Kowsi's KWS-DC28 is an inline power meter using 5.5 × 2.1/2.5mm DC jacks. It displays voltage, current, time and more on a compact colour OLED screen.

This portable pressure washer with two 21V Li-ion batteries was just £12 from Temu. It's very handy for power-washing and spot-cleaning.

Powerful Motor
21V
LI-ON BATTERY
21V
LI-ON BATTERY

It uses 5.5 × 2.1/2.5mm DC jacks at both ends, which will fit most ordinary mains adaptors. I found some characters on the colour display tiny and hard to read, though. The device cost less than £5.

Last up this month, with autumn and winter cleanups in mind, the subject of pressure washers came up. Useful for cleaning muddy cars, trucks, driveways, paths, drains or outdoor furniture, they're the sort of machine you keep finding uses for once you've owned one. So I hope the following 'heads-up' might interest readers who already have one.

While they can't match a mains-powered machine for cleaning power, portable low-voltage pressure washers are catching on. TV advertising might exaggerate their performance a bit, since they prove best mainly for power rinsing and washing. I found they won't remove baked-on brake dust from alloy wheels, for example. Still, they are more convenient to use than a mains-powered one.

My Ryobi One+ 18V pressure washer, costing £120, failed dismally after less than two years. I then found that some traders selling through Temu were listing some tempting money-saving alternatives.

An unbranded, battery-powered machine, as seen widely on TV shopping channels for £55, came in at just £12 (!), complete (happily) with two 21V lithium-ion batteries, a bucket hose, foam sprayer and mains charger. If it only lasts two years, I'll be satisfied.

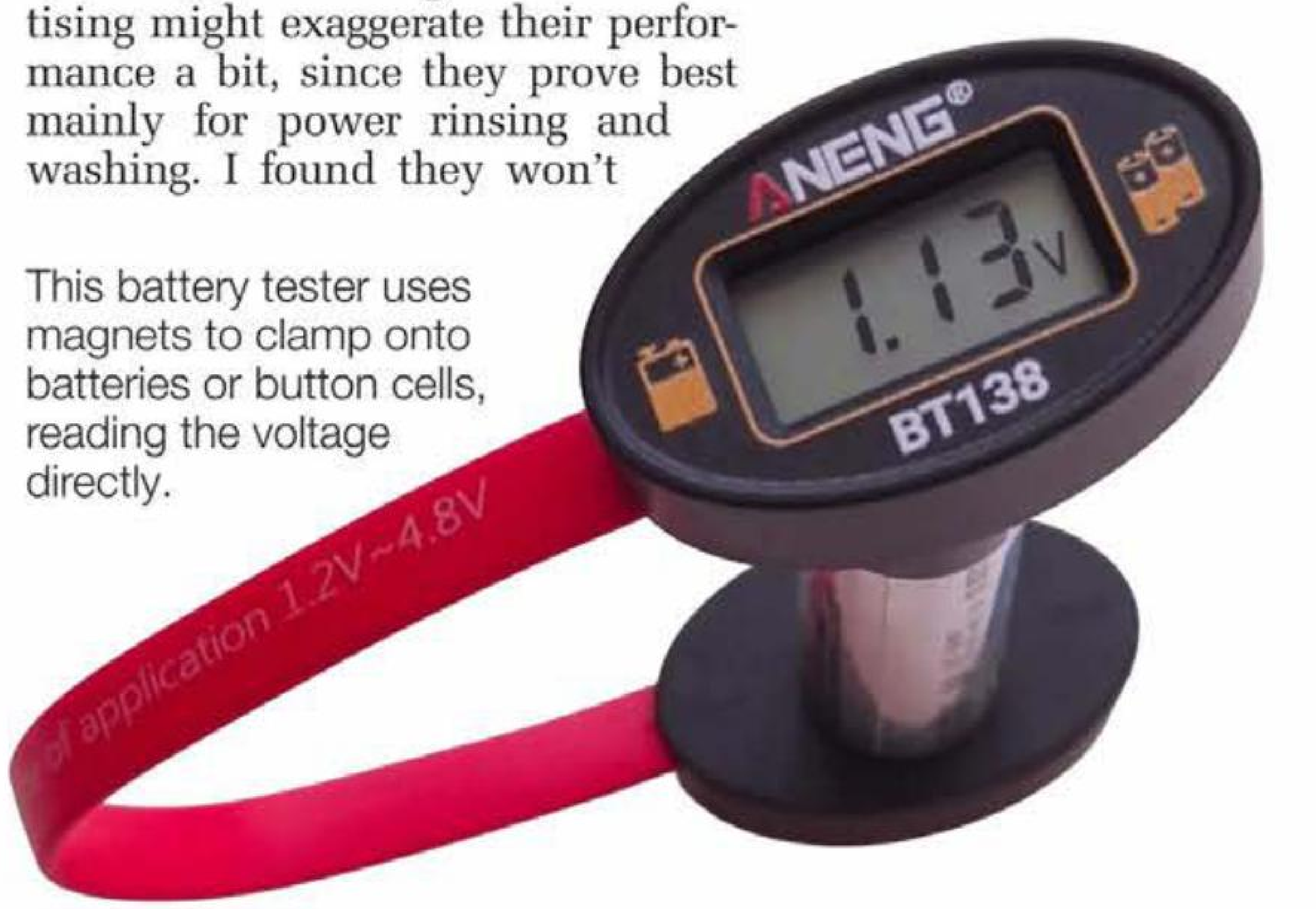
These machines employ so-called ¼-inch (6.35mm) 'quick connect' fittings, which are starting to appear on the UK market. Extension lances, a wheeled pathway/car chassis cleaner and colour-coded spray nozzles duly followed, all at very affordable prices.

Spares, extension hoses and quick-connect adaptors for Kärcher machines are also sold on Temu, so I also upgraded my machine to use Kärcher's latest bayonet fittings, all for just a few pounds. Finally, I could clean my 25-foot-high house eaves!

I then spotted identical 21V batteries used on other Chinese-made DIY gear, including power drills, loppers, grinders and mini chain saws. It's definitely something worth bearing in mind when equipping your workshop.

Meanwhile, fearing some possible winter chaos and power cuts, I've sourced a very efficient little gas heater from Temu for just £17! [It would be worth investing in a CO alarm at the same time – Editor]

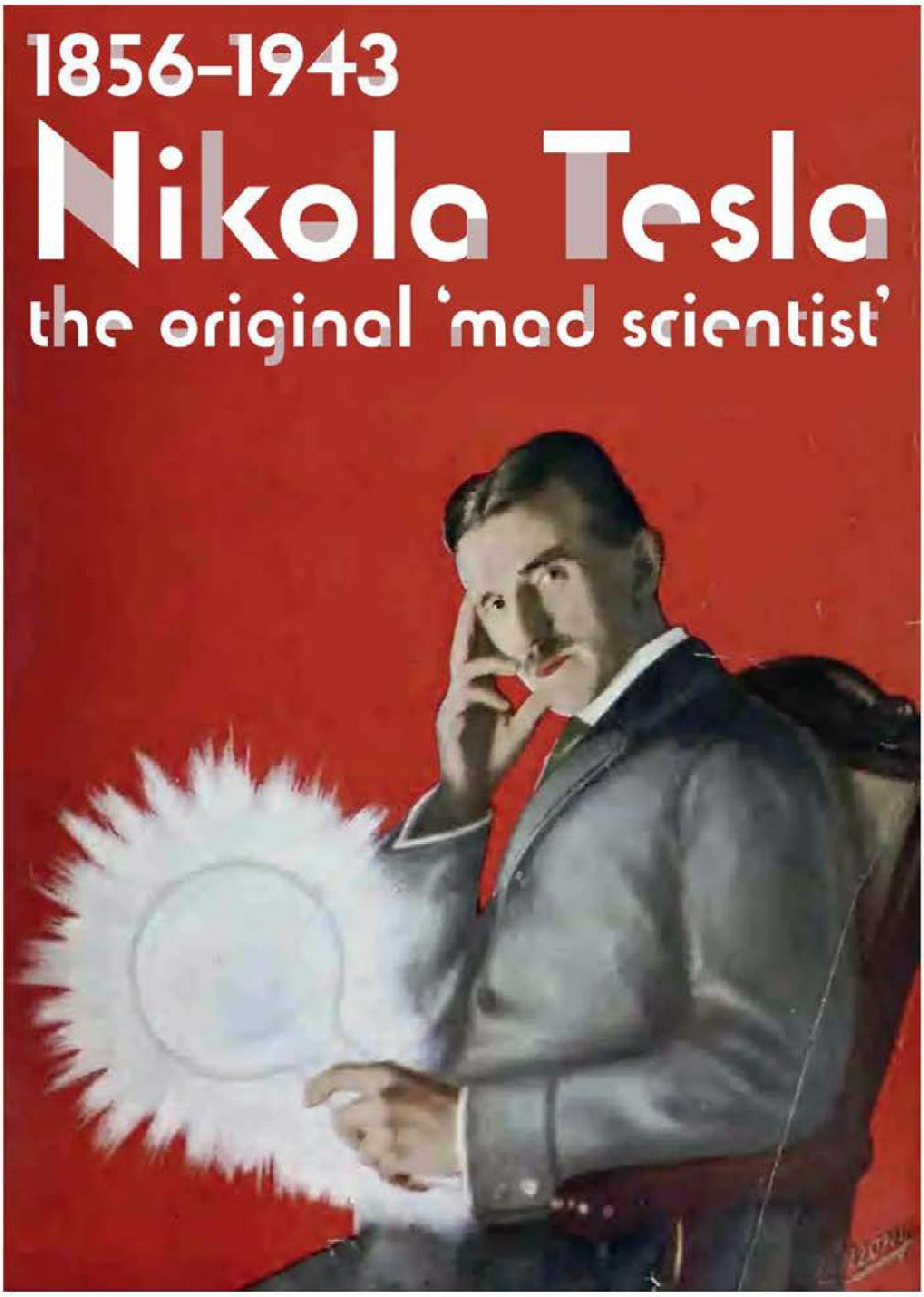
That's all for this month. Don't forget the above links are ready-made for you on the *Net Work* blog at **electronpublishing.com**. Join me next time for more *Net Work*. As always, I can be reached at **alan@epemag.net**



This battery tester uses magnets to clamp onto batteries or button cells, reading the voltage directly.

¼-inch 'quick connect' nozzle fittings are now arriving in the UK.

1856–1943
Nikola Tesla
the original 'mad scientist'



The first article in this two-part series, published last month, introduced prolific inventor Nikola Tesla and covered his life and developments until 1898 before we ran out of space. This article picks up where that one left off and also covers some overarching topics, like his contributions to AC electricity and some of his misconceptions.

Part 2 by Dr David Maddison, VK3DSM

Tesla on the cover of Electrical Inventor magazine, February 1919. The lead image is based on a photo of Tesla from around 1900 demonstrating wireless power transmission. He is holding a partially evacuated glass bulb that's glowing due to the electric field from a nearby Tesla coil. See https://w.wiki/AZMz

Last month, our final entry concerned Tesla's application for multiple radio patents in 1897 and some of the controversy surrounding his claims predating some of Marconi's, despite Tesla not having demonstrated any real radio communications. Here is what happened after that:

Ignition system for gasoline engines
1898

In 1898, Tesla obtained US Patent 609,250 for a spark plug for petrol engines – see Fig.14.

Teleautomatics
1898

Tesla received US Patent 613,809 for a remote-controlled vehicle in 1898 (Fig.15), titled "Method of and Apparatus for Controlling Mechanism of Moving Vessels or Vehicles". Based on this, he demonstrated a remote-controlled 1m-long boat at Madison Square Garden in New York City as part of the first annual Electrical Exhibition.

The boat was controlled by an operator with a transmitter (see Fig.16). The receiver used a device called a coherer, an early type of radio signal detector containing metal filings that came into contact with each other when a radio signal was received, changing its resistance. Once a signal was received, the device had to be reset by shaking it or using a 'clapper' attached to an electromagnet.

Such a device could only detect the presence or absence of a signal, like in Morse code; such a binary output was ideal for this application. One of Tesla's inventions was a coherer that continuously rotated to reset it, although he does not use the term "coherer".

The boat contained a motor for propulsion and one for a servo mechanism. The boat could steer, start, stop, go forwards or backwards or light one of two lamps.

To control the boat, there was a mechanism that, upon detecting the radio signal, moved a set of electrical contacts to the next of several positions that would execute the predefined manoeuvre. This represented the state of the rudder, motor and lighting.

Radio signals from Mars
1899

Tesla believed that radio signals he received in 1899 in Colorado may have been from Mars (see Fig.17). In 1909, he wrote:

To be sure, we have no absolute proof

that Mars is inhabited... Personally, I base my faith on the feeble planetary electrical disturbances which I discovered in the summer of 1899, and which, according to my investigations, could not have originated from the sun, the moon, or Venus.

Further study since has satisfied me they must have emanated from Mars – ***https://pemag.au/link/aby4***

Some have suggested that the signals Tesla was receiving were, in fact, from Marconi's (or others') radio experiments.

Tesla Experimental Station
1899 to 1900

In 1899, Tesla established the Tesla Experimental Station in Colorado Springs, Colorado, and used it for one year. He moved there because he wanted a high altitude for his experiments in wireless electricity transmission and more space than his Manhattan laboratory. His main focus was on high-frequency, high-voltage experiments.

He built the largest Tesla coil to date, with a diameter of 15m, to be configured as a "magnifying transmitter". This was a variation of the Tesla coil with an antenna (see Fig.18) tuned to the supposed resonant frequency of the Earth to create standing waves of electrical energy. The idea was to harvest them with an appropriate antenna and receiver.

The magnifying transmitter was a three-coil, triple-resonant design. This coil reportedly had a 300kW power rating and generated millions of volts at 150kHz. This was to be the prototype for his magnifying transmitter at the Wardenclyffe Tower.

Tesla produced electric arc discharges up to 41m long. He had a deal with the local power company to provide large or unlimited amounts of power (he occasionally damaged their generators!). Tesla wrote that he had produced 20MV at 1000-1100A (we assume that was current drawn from the mains supply) and that he had learned how to produce 100MV (see p196, **https://pemag.au/aby0**).

Tesla also wrote that lightning arrestors on buildings within a 19 km radius were "bridged with continuous arcs" and that he lit handheld incandescent lights 15-30m from his laboratory when the oscillator was running at 4MV. Apparently, the light filament often broke due to the resulting vibrations.

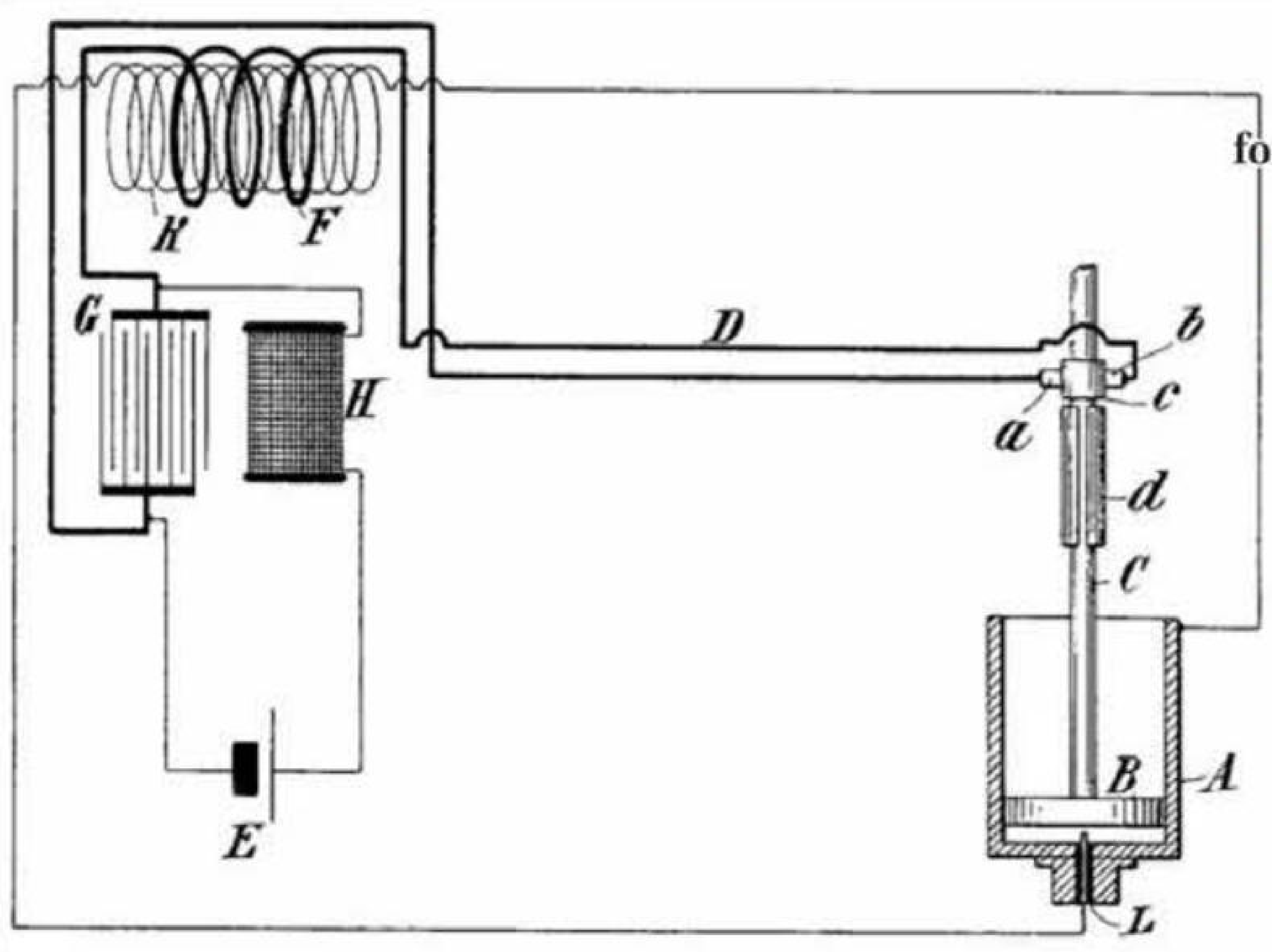


Fig.14: Tesla's ignition system for petrol engines. ***Source: https://patents.google.com/patent/US609250A***

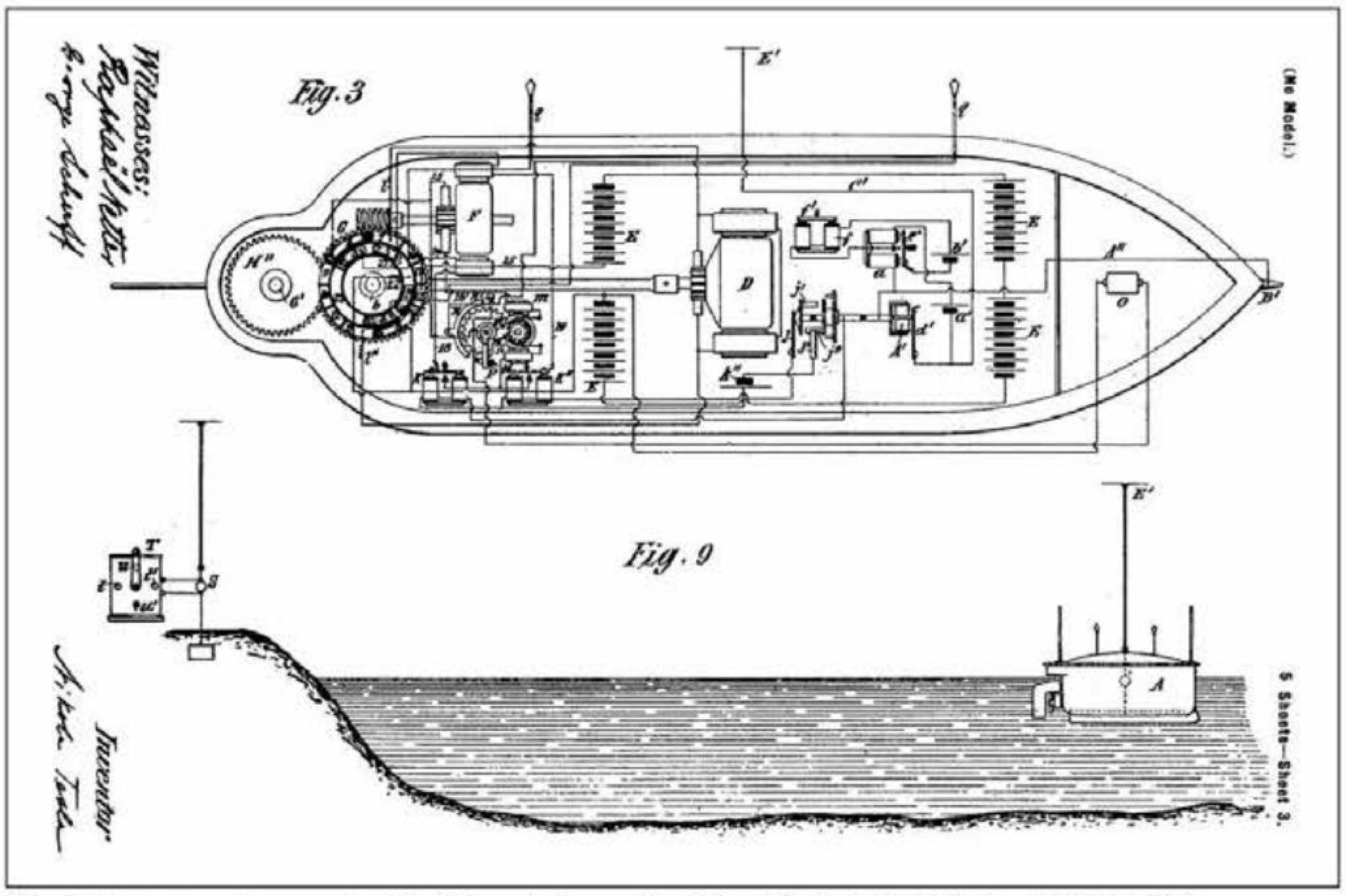


Fig.15: a remote-controlled boat described by Tesla's US Patent 613,809 (top: plan view, bottom: the vessel in the water).

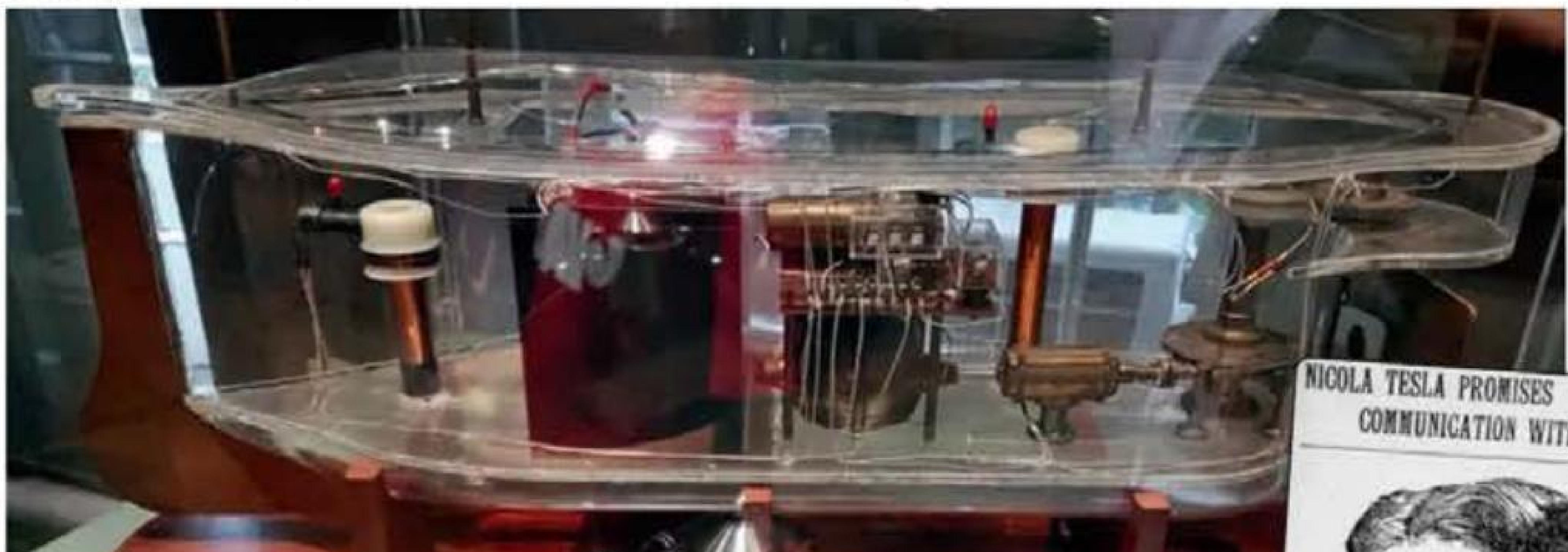


Fig.16: a model of Tesla's boat in the Nikola Tesla Museum in Belgrade. The museum website (https://tesla-museum.org/en/qr-en/exhibit-049) gives no information about when the model was made, but clear acrylic wasn't invented until the 1930s. ***Source: https://w.wiki/AbUv***

NICOLA TESLA PROMISES
COMMUNICATION WITH MARS.

Fig.17: a newspaper article titled "Nicola Tesla Promises Communication with Mars" from The Times (Richmond, Virginia, USA) on January 13th, 1901, page 8. ***Source: The Times, January 13th 1901 – https://pemag.au/link/abyo***

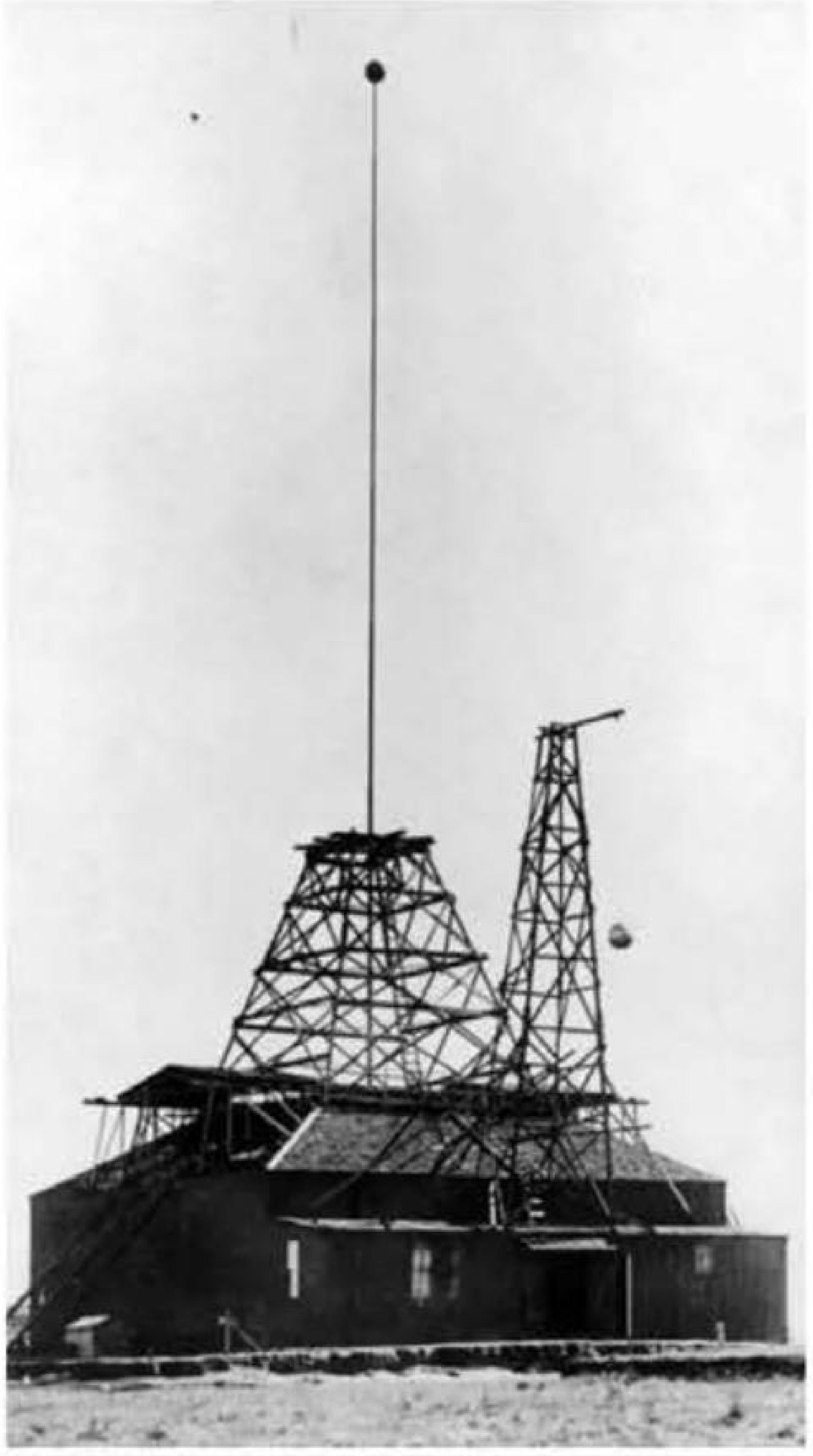


Fig.18: an exterior view of the Colorado Springs laboratory. The antenna mast was telescopic and 43m tall. *Source:* https://w.wiki/AbUx

Tesla stated that when he energised the large transmitter coil, butterflies were caught in the field and flew around in circles as if trapped in a hurricane. He also noted sparks in the sand when walking "some distance from the building", saying:

> *At night a continuous stream of tiny sparks could be seen between the heels and the earth and between the grains of sand.*
>
> *When I operated with undamped waves, the oscillator being perfectly silent (no streamers whatever), a horse at a distance of perhaps one-half a mile, would become scared and gallop away the instant the switch was thrown on... When using damped waves the roar was so strong that it could be plainly heard ten miles away.*

Fig.19 was a long-exposure photo taken in a darkened room. The arcs are for demonstration purposes, deliberately induced and were not a normal part of the operation of this machine. The discharge was reported to be deafening and that "sparks an inch long can be drawn from a water main at a distance of three hundred feet from the laboratory".

The laboratory was torn down in 1904, and the contents were sold to pay off debts.

Energy harvesting
1901

In 1901, Tesla was granted US Patent **685,957** for supposedly harvesting energy from sources such as "ultra-violet light, cathodic, Roentgen rays, or the like".

Wardenclyffe Tower
1901 to 1906

Wardenclyffe was Tesla's last major laboratory (see Figs.20 & 21). It was built in Long Island, New York and was intended for trans-Atlantic wireless communications. Later, he wished to extend it for wireless power transmission in accordance with his theories.

Banker JP Morgan was the main financial backer for this project, but he refused to continue funding it. So it was abandoned in 1906, never having become operational.

The tower was, to some extent, an extension of Tesla's Colorado Springs experiments in an attempt to implement the World Wireless System for transmitting electric power.

Tesla believed that if he injected current into the Earth at the right frequency, he could get the Earth's natural charge to resonate and establish standing waves, which could be utilised to harvest electricity remotely. At Wardenclyffe, iron pipes were sunk 37m into the ground, and the tower was 57m tall.

The tower was believed to be also intended to have ultraviolet lights on top, possibly to create an ionised pathway to conduct electricity to the upper atmosphere.

After JP Morgan's final refusal to continue to fund the project, Wikipedia

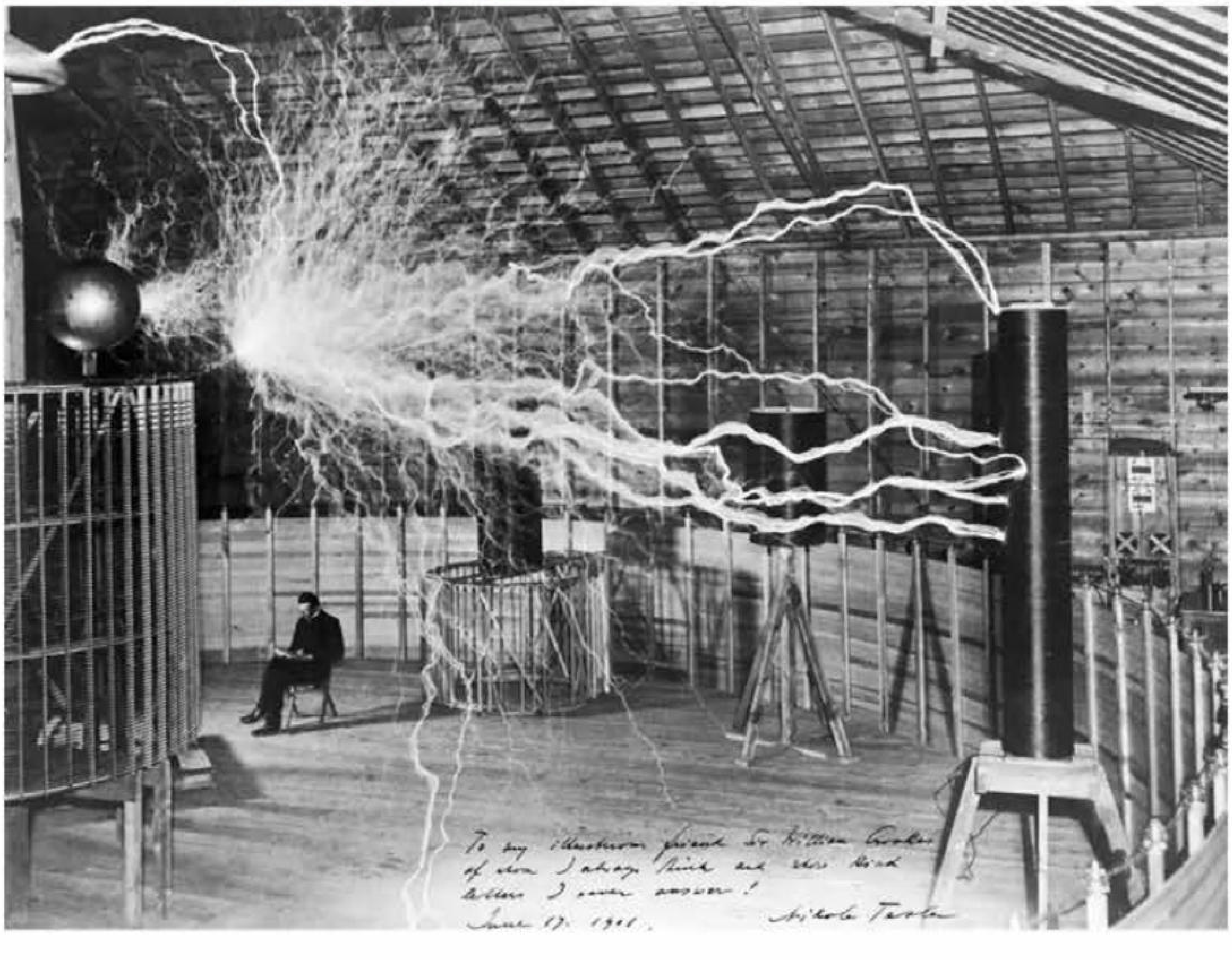
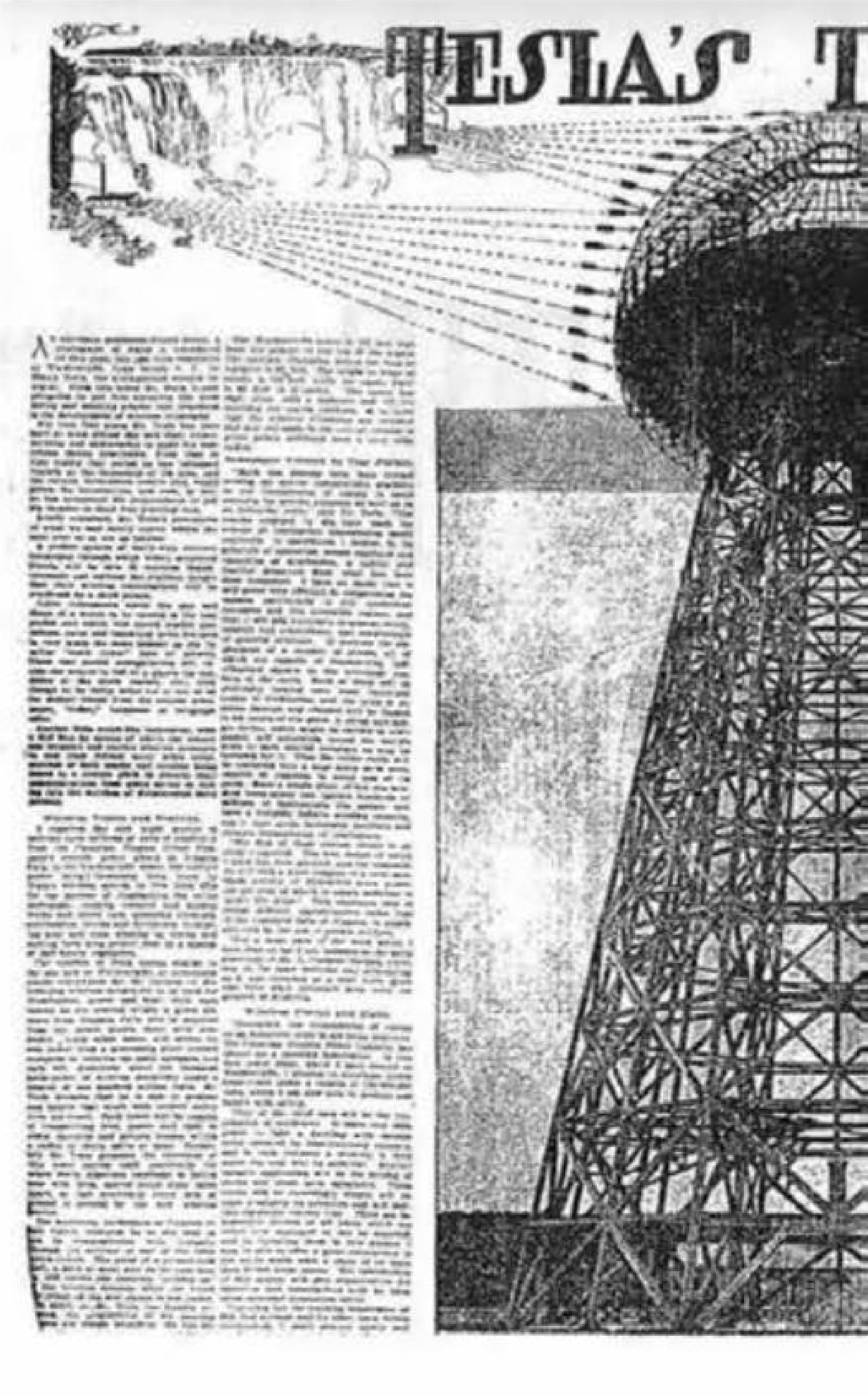

To my illustrious friend Sir William Crookes
of whom I always think and whose kind
letters I never answer!
June 17. 1901.
Nikola Tesla

Fig.19: Tesla's "magnifying transmitter" at his Colorado Springs facility, around 1899. This photo was a long-exposure photo taken in a darkened room with a double exposure showing Tesla sitting on a chair. *Source:* https://w.wiki/AbUw



notes, "newspapers reported that the Wardenclyffe tower came alive shooting off bright flashes lighting up the night sky. No explanation was forthcoming from Tesla or any of his workers as to the meaning of the display, and Wardenclyffe never seemed to operate again" (also see the website www.teslasociety.com/warden.htm).

Even before the tower project's failure, investors had lost interest in Tesla. They were more interested in Marconi, who transmitted a Morse code wireless signal from England to Newfoundland in 1901.

The failure of the Wardenclyffe project led Tesla to have a nervous breakdown in 1905. Apart from the withdrawal of financial support by JP Morgan, Tesla may have had doubts about whether his science was correct. Biographer Bernard Carlson wrote:

> *Tesla faced a serious dilemma... Either he was wrong or nature was wrong.*

Wireless electricity transmission

1905

In the January 7th 1905 issue of *Electrical World and Engineer*, Tesla wrote about how he saw wireless transmission of electricity as a means of furthering world peace (p85, https://pemag.au/aby0).

Wireless communications

1905

In 1905, he received US Patent 787,412 for the "Art of transmitting electrical energy through the natural mediums". He described "stationary waves" from lightning at a 25-70km wavelength that "may be propagated in all directions over the globe".

He proposed reproducing this to transmit messages and establish positional data. He anticipated that resonances would occur at greater than 6Hz.

Predictions

1911

According to the *New York American* on the 3rd of September 1911, Tesla's "World System" (Fig.22) would perform the following tasks. We will comment on the status of each.

- **Television, making it possible to see any object at any distance.**

> *Yes.*

- **Universal twenty-four-hour daylight by wireless illumination.**

> *No, although there is plenty of night-time lighting.*

- **Instantaneous transmission of typed or hand-written characters all over the world.**

> *Yes.*

- **Operation of flying machines by wireless power.**

> *No, but solar-powered aircraft exist, as do some experimental remotely-powered drones. For more details, see the Silicon Chip magazine article on Aerial Platforms (August 2023; siliconchip.au/Article/15894).*

- **Navigation of ships through fogs and channels by wireless "tuned" compasses.**

> *Yes.*

- **Communication with Mars.**

> *Yes, in the sense that we can send and receive radio signals to and from spacecraft on Mars.*

- **Operation of all manufacturing and transportation machinery.**

> *Yes, if it means remote wireless or autonomous operation of machinery.*

- **Every clock and watch in the world set and regulated by wireless at certain time each day.**

> *Yes, that is certainly possible now.*

- **Universal telephony, making it possible to speak at any distance.**

> *Yes.*

- **A perfect government secret signal service by exclusive wireless waves.**

> *It is essentially possible now by using strong encryption.*

- **Simultaneous operation of all stock tickers throughout the world.**

> *Yes.*

- **Universal system of musical transmission on atmospheric currents.**

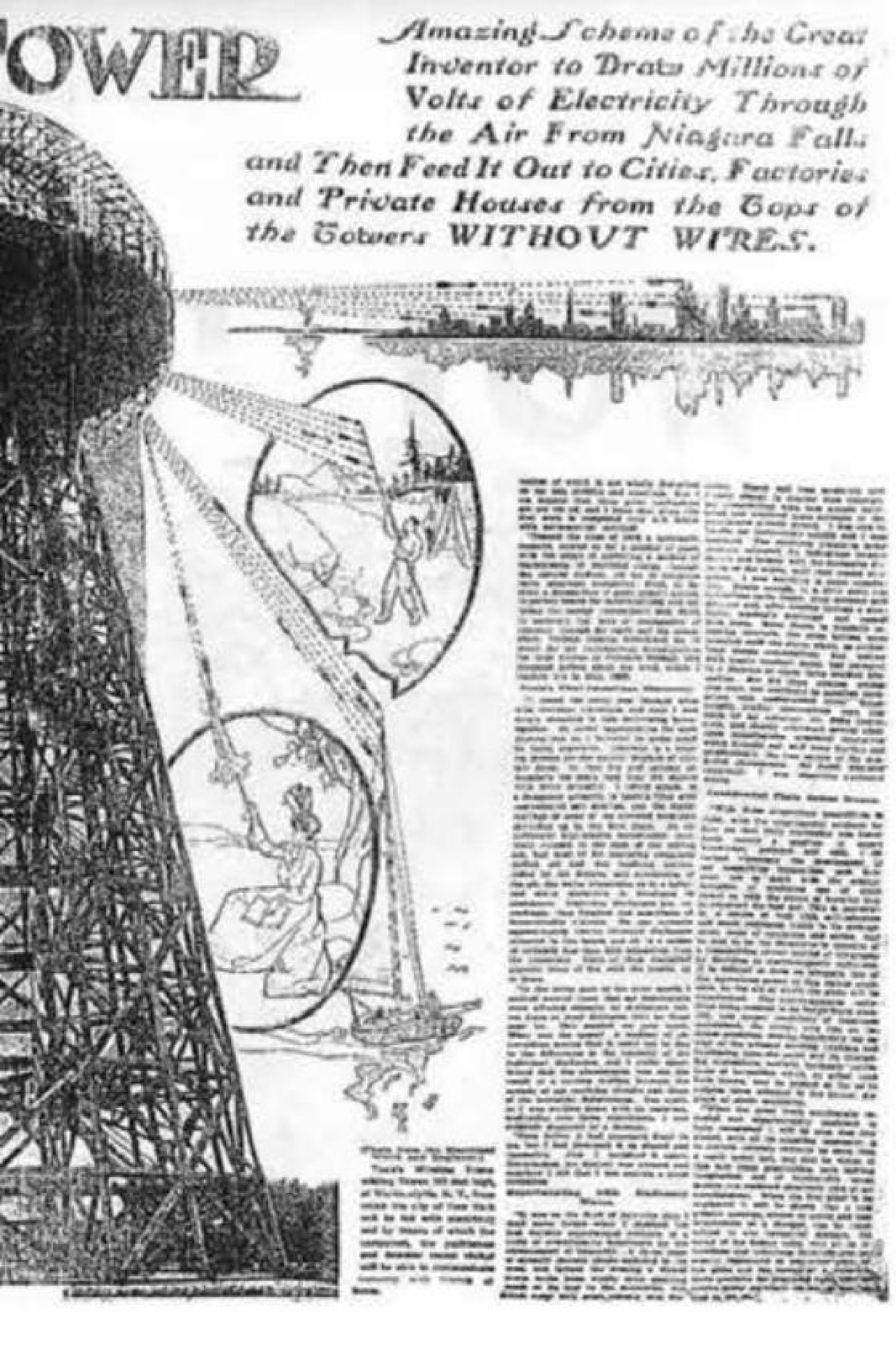
> *Not exactly, although radio can transmit music over very long distances.*

- **Irrigation and fertilization of arid lands by wireless power.**

> *No, that amount of wireless power is not practical.*

- **The magnetizing of enemy's battleships to attract torpedoes.**

> *No, although magnetism is used to detect ships.*



OWER

Amazing Scheme of the Great Inventor to Draw Millions of Volts of Electricity Through the Air From Niagara Falls and Then Feed It Out to Cities, Factories and Private Houses from the Tops of the Towers WITHOUT WIRES.

Fig.20: a newspaper article about Wardenclyffe Tower from the New-York American, May 22nd, 1904. ***Source:* https://w.wiki/AbUz**

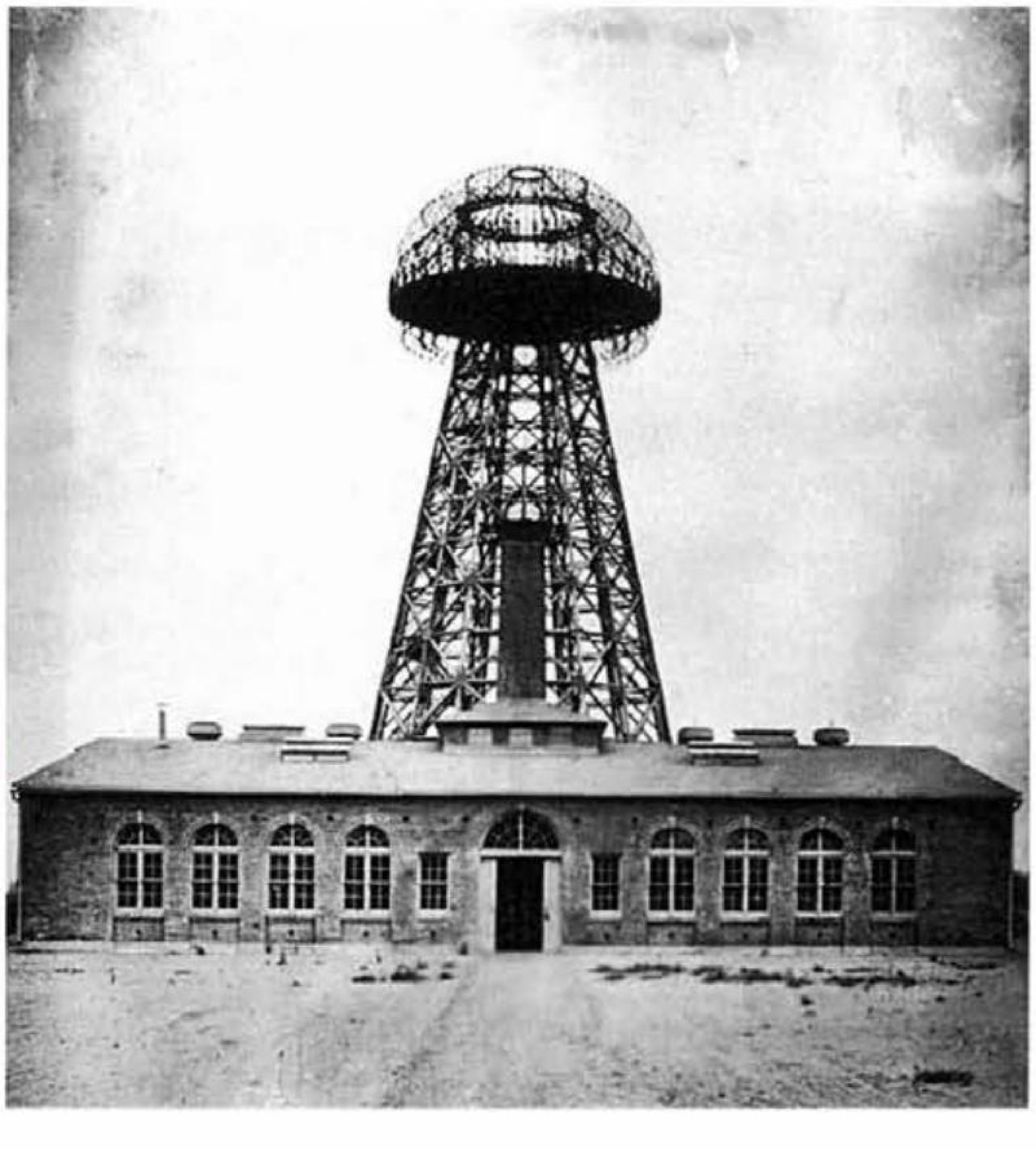


Fig.21: Wardenclyffe Tower in 1904. The tower was 57m tall but was never finished due to a lack of funding. The top of the tower was meant to be a smooth dome. ***Source:* https://w.wiki/AbU$**

- **Reproduction of drawings and photographs at any distance.**

> *Yes.*

- **Absolutely exclusive telegraphy and telephony.**

> *Yes (encrypted communications).*

Tesla turbine
1913

In 1913, Tesla received US Patent 1,061,206 for a novel bladeless turbine in which the working fluid impinged tangentially on a stack of discs. The fluid causes the discs to rotate via the laminar flow of the fluid at the disc surface, and thus, it extracts energy from the working fluid, such as steam or water (see Figs.23 & 24).

The fluid enters the stack of discs at the edge and is exhausted at the centre. The turbine was said to be more efficient, simpler, could run faster and at higher temperatures than bladed axial turbines of the time. It could also be used as a pump. The turbine has seen little commercial application, probably because its advantages have been difficult to realise in practice.

For more on this, see the video titled "The Tesla Turbine & How it Works" at https://youtu.be/mrnul6ixX90

Wireless transmission of electricity
1914

In 1914, Tesla was granted US Patent 1,119,732, which improved upon his previous power transmission schemes. While the size of the power transmission structure shown in Fig.25 is not specified, we expect it would be a large tower similar to what was (incompletely) built at Wardenclyffe and similar to the modern one pictured in Fig.26.

Speedometer
1916

In 1916, Tesla was granted US Patent 1,209,359 for a speedometer. He licensed it to Waltham Watch, which sold 60,000 copies.

Wardenclyffe Tower dismantled
1917

In 1917, the metal tower was demolished for its scrap metal value to help pay Tesla's debts and the property was foreclosed in 1922. The original brick building remains and has been converted into a museum and educational science centre, partly with the aid of Elon Musk. See:

https://teslasciencecenter.org/

Finding hidden submarines
1917

In his proposal to find enemy submarines, he wrote, "I believe this magnetic method of locating or indicating the presence of an iron or steel mass might prove very practical in locating a hidden submarine." This article was published in *The Electric Experimenter* in August 1917. It turned out to be a practical idea, used widely during WW2.

Allis-Chalmers
1918-1920

During this period, Tesla worked with the steam and gas turbine manufacturer Allis-Chalmers, testing 200kW and 500kW steam turbines. The results were unsatisfactory, and Tesla also said the working conditions were poor, so the collaboration soon ended.

Tesla fluid valve
1920

In 1920, Tesla was awarded US Patent 1,329,559 for a "valvular conduit",

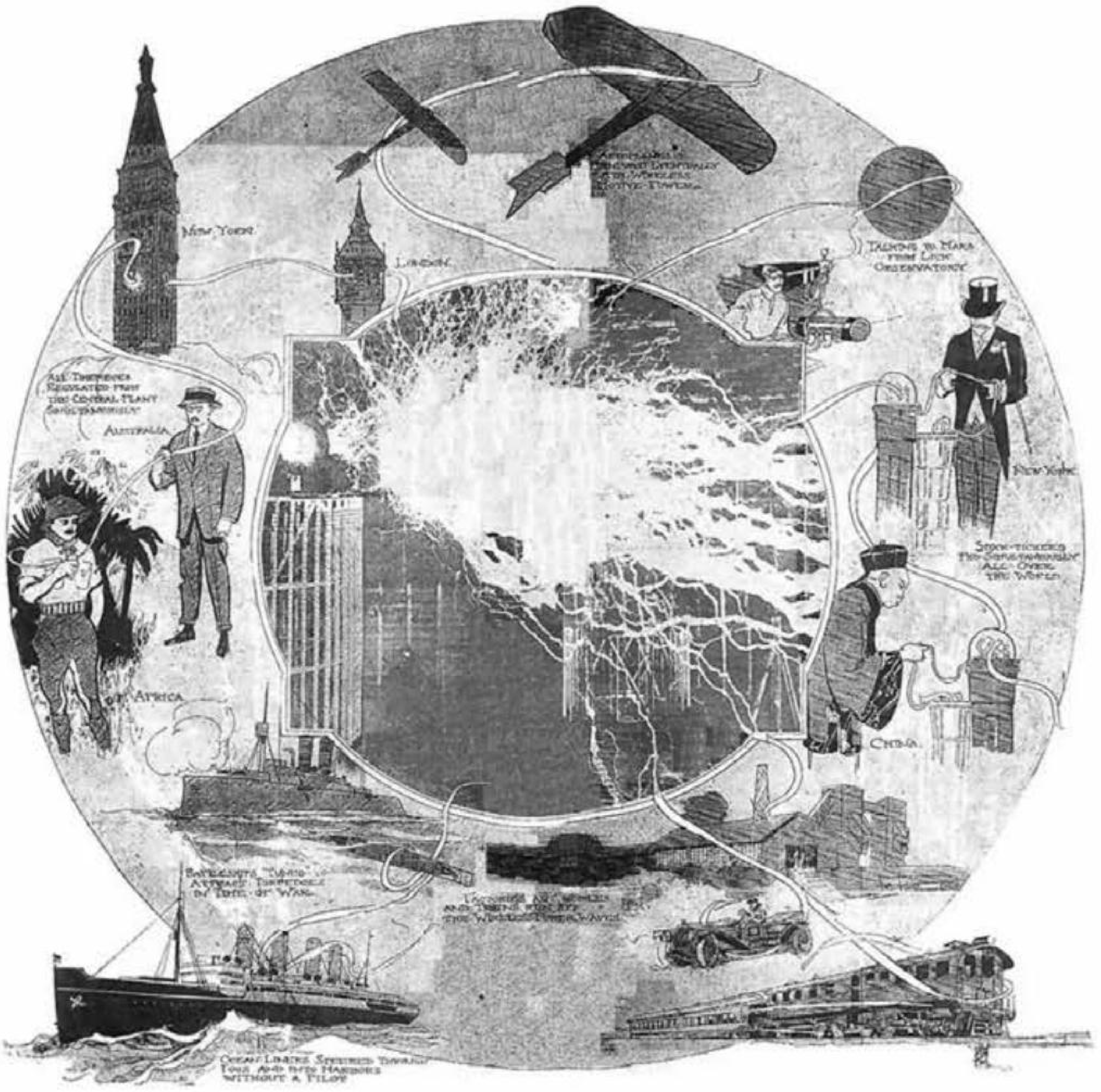


Fig.22: an illustration from the article in the "New York American" of 3rd of September, 1911 on Tesla's "World Wireless System", entitled "To Turn Earth into One Gigantic Dynamo". *Source:* *https://teslauniverse.com/nikola-tesla/articles/turn-earth-one-gigantic-dynamo*

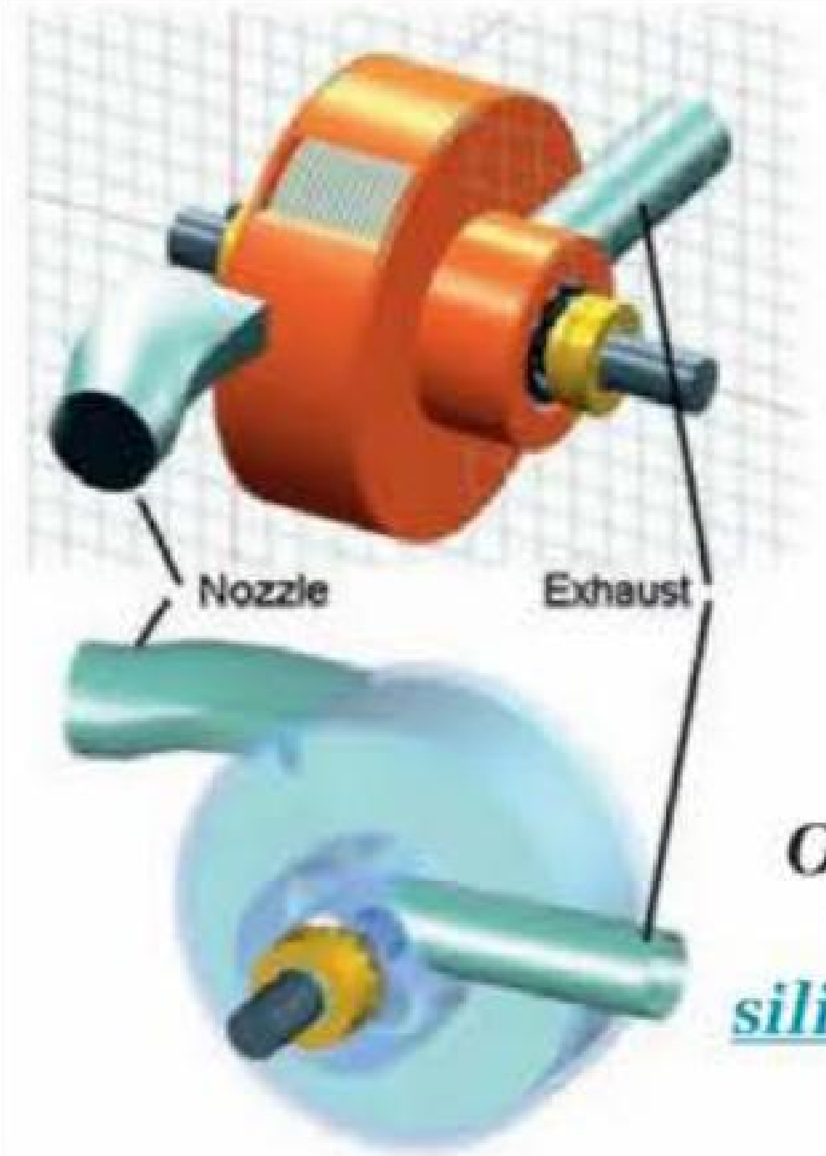


Fig.23: a drawing of the Tesla turbine. *Source: Open Source Ecology – siliconchip.au/link/abyp*

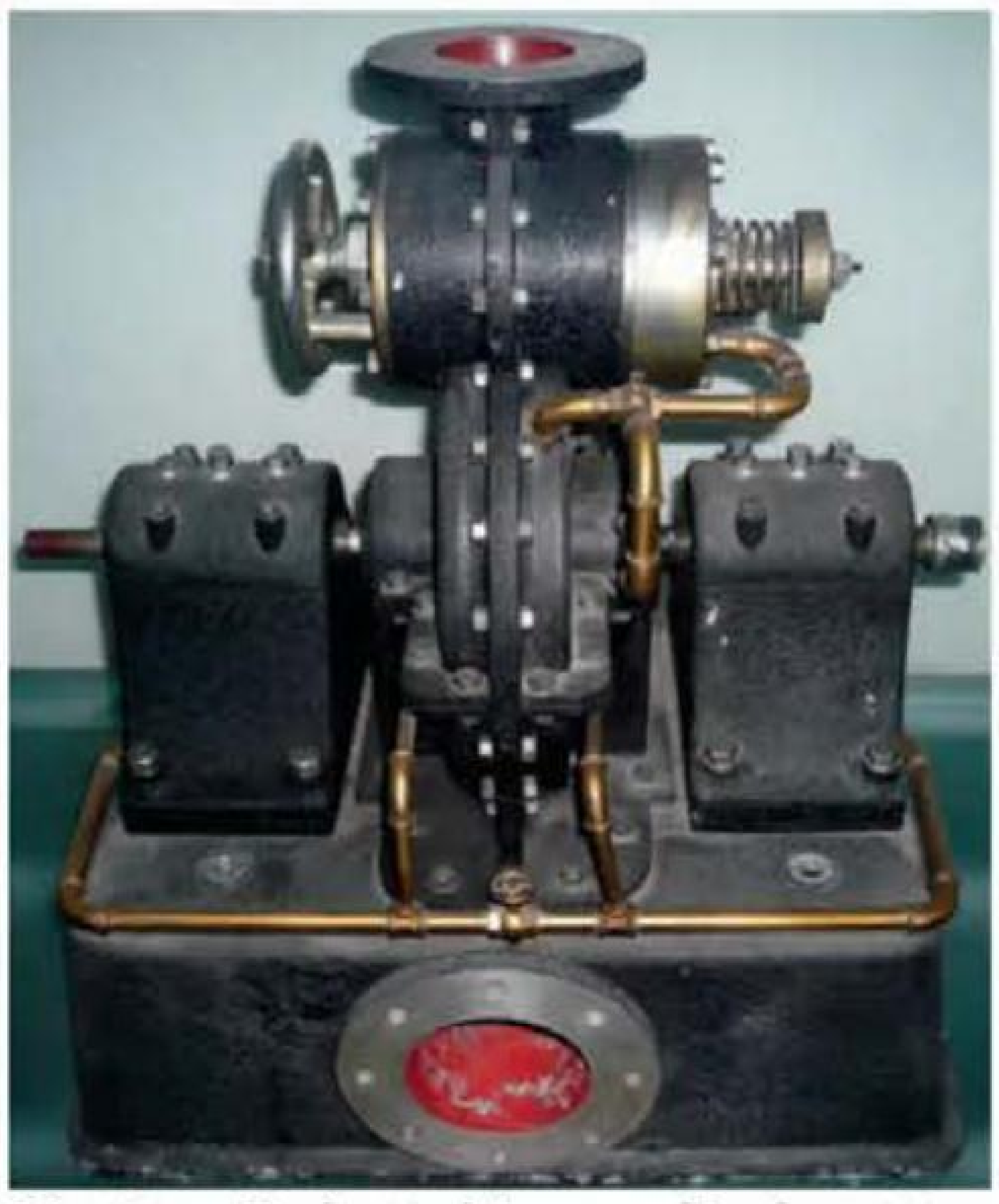


Fig.24: a Tesla turbine on display at the Nikola Tesla Museum, Belgrade. *Source:* https://w.wiki/AbV2

which causes the fluid flow to be relatively unimpeded in one direction but highly impeded in the opposite direction. It is the fluid equivalent of a diode (see Fig.27).

The device has no moving parts and is scalable from microfluidic applications upward. However, the fluid needs a certain minimum flow speed for it to work effectively. Today, there is renewed interest in the valve and its applications, including its use in microfluidics (see the article on that in the August 2019 issue of Silicon Chip at siliconchip.au/Article/11762).

Xiaomi uses it in its "loop liquid-cool technology" for mobile phones (https://pemag.au/link/aby5). It is also used in a steam mop (https://youtu.be/rYdtf90CcJQ) and a blood viscometer (https://pemag.au/link/aby6).

Sulfur processing

1923

In 1923, Tesla was granted two US Patents (645,568 & 645,569) for treating and transporting sulfur, but he failed to pay the fees, and the patents were withdrawn.

VTOL aircraft

1928

In 1928, Tesla received his final patent, US Patent 1,655,114 for what he described as "a new type of flying machine, designated 'helicopter-plane', which may be raised and lowered vertically and driven horizontally by the same propelling devices" – see Fig.28.

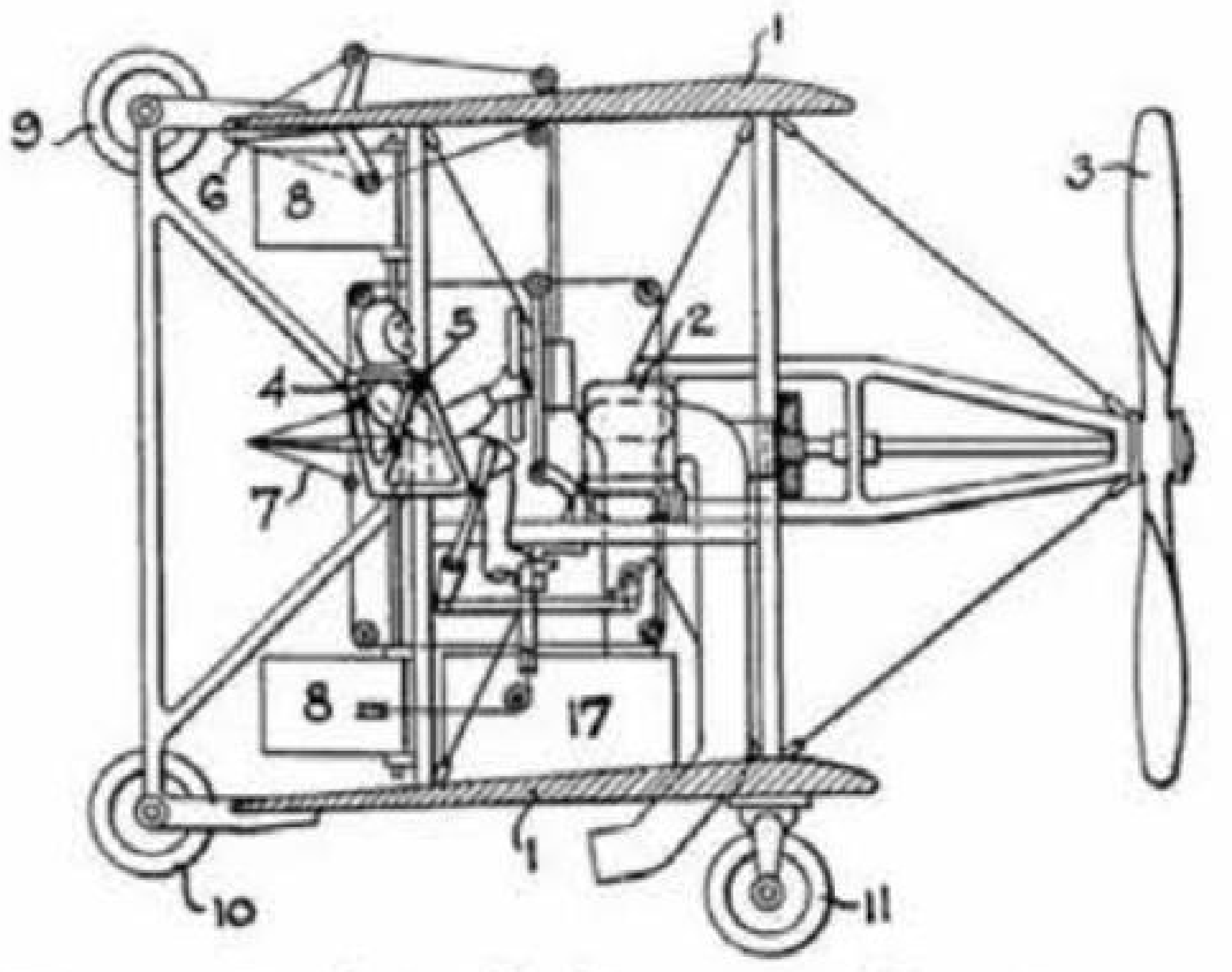


Fig.28: Tesla's "helicopter-plane" drawing from US Patent 1,655,114.

Electric car (hoax)

1931

There were claims that in 1931, Tesla made an electric car powered by a "cosmic energy power receiver" without a battery. These are false and no such machine was ever made.

Ocean & geothermal energy

1931

Tesla suggested improvements to existing ideas to harvest geothermal energy from within the Earth. His idea was to pump water down a borehole, where the internal heat of the Earth at sufficient depth would turn it into steam, after which it returns and drives a turbine to generate electricity, condenses and is then returned to the borehole to continue the cycle (see Fig.29).

He also suggested improvements to existing ideas for energy generation by harvesting heat differentials between the deep and shallow parts of the ocean. A working fluid would be vaporised at a higher temperature, drive a turbine, and then condense at a lower temperature.

Breaking up tornadoes

1933

In 1933, Tesla proposed using a radio-controlled aircraft to carry

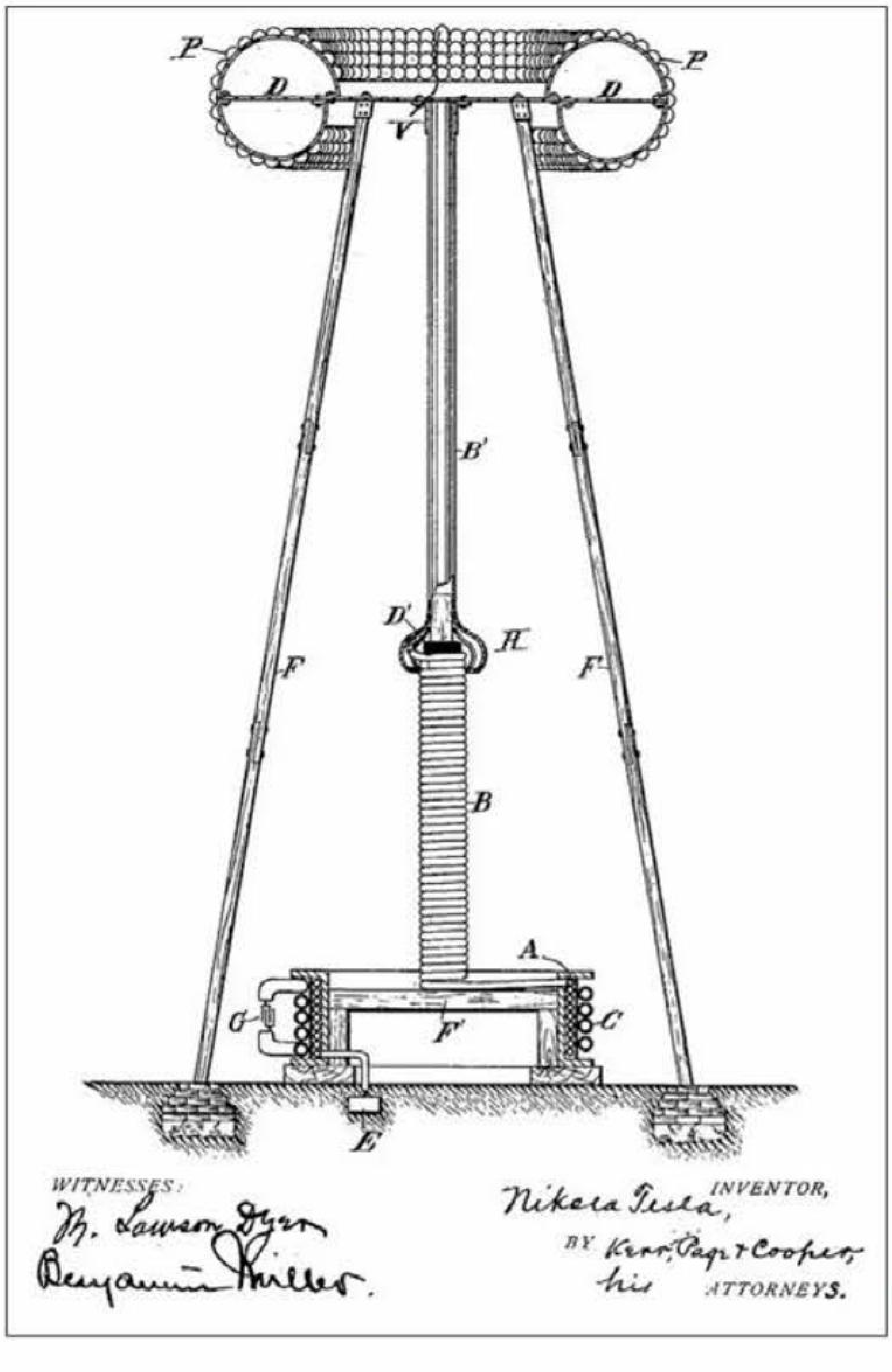


Fig.25: the terminal structure, coil, capacitor and other components for radiating electrical energy, from Tesla's 1914 US Patent 1,119,732 regarding wireless power transmission.

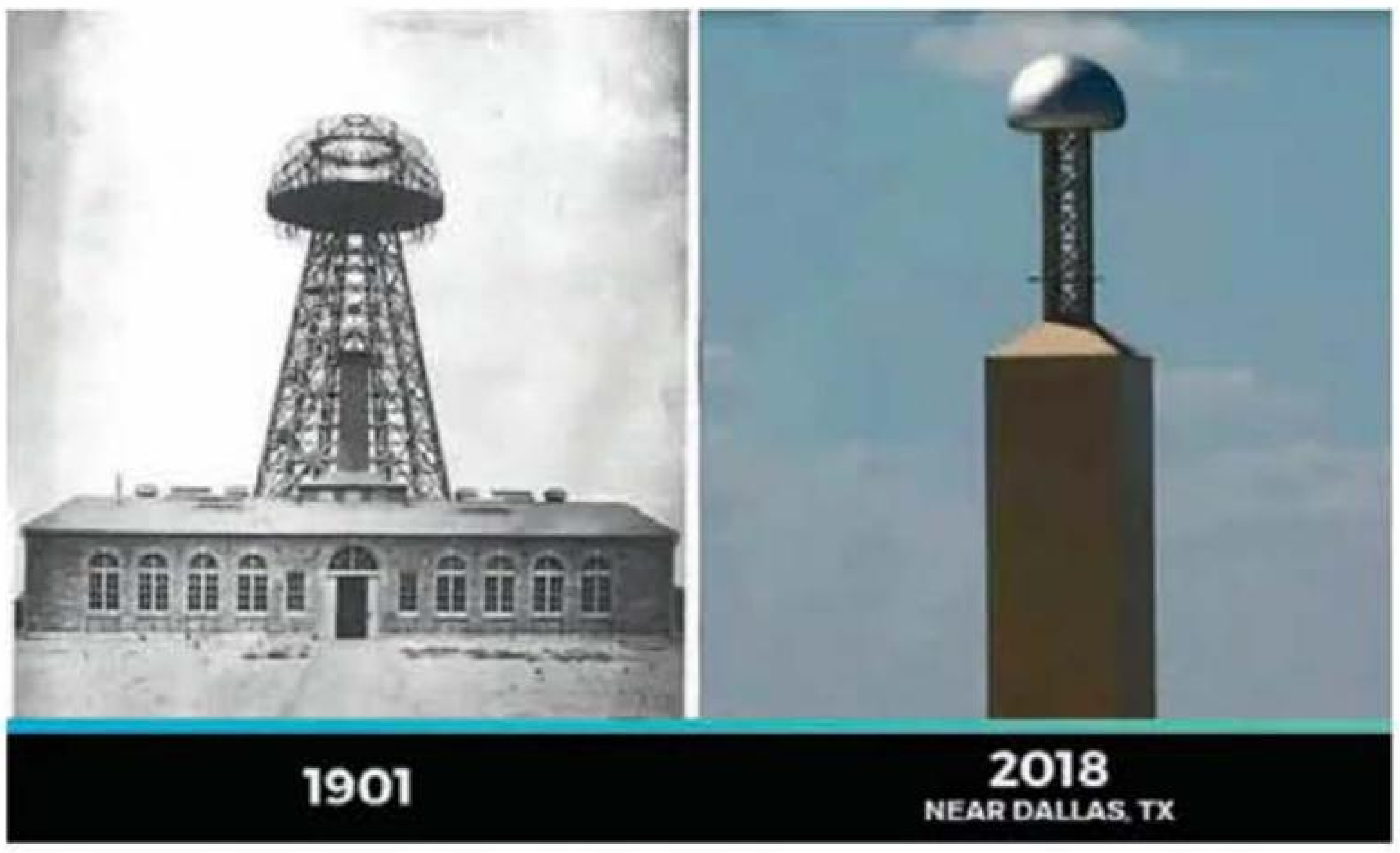


Fig.26: Tesla's Wardenclyffe wireless power transmission tower (1901) and Viziv's tower (2018). ***Source: Stack Exchange – https://pemag.au/link/abyq***

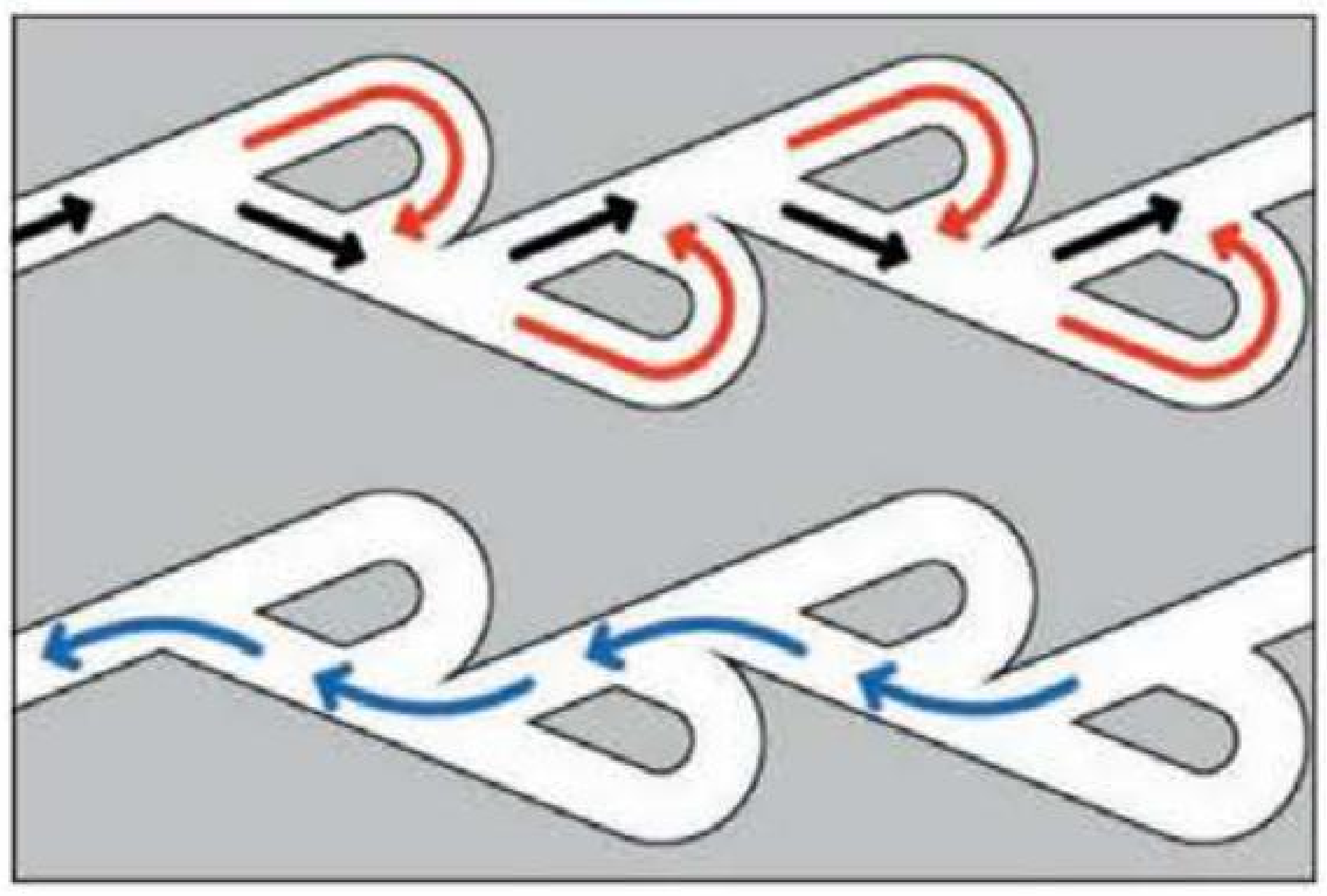


Fig.27: at the top, fluid travels from left to right and is blocked because part of the fluid stream is turned around and interferes with the other part. Below that, fluid is travelling from right to left and is unimpeded. ***Source: https://w.wiki/AbV3***

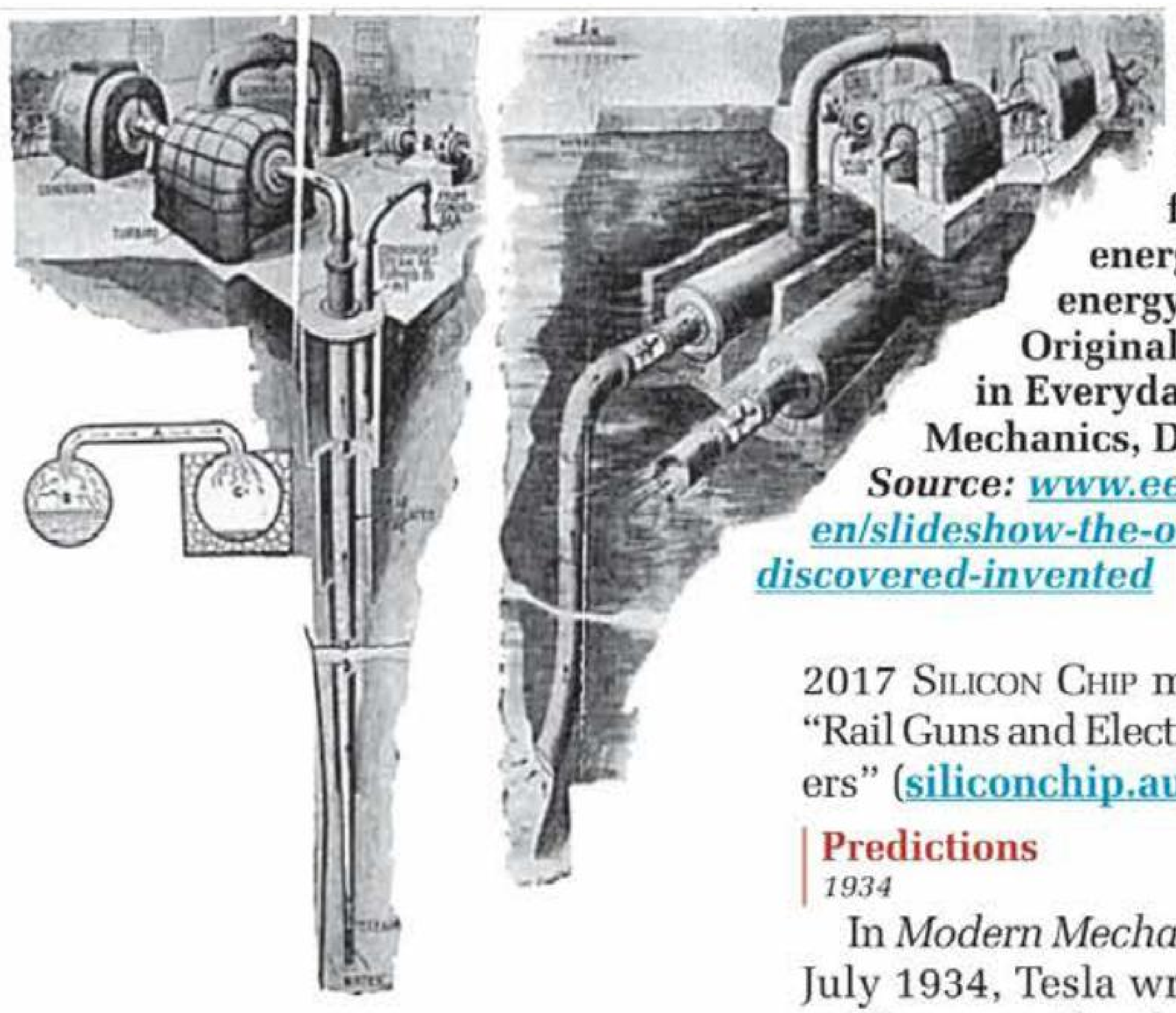


Fig.29: Nikola Tesla proposed improvements to existing ideas for geothermal energy (L) and oceanic energy (R) harvesting. Originally published in Everyday Science and Mechanics, December 1931. *Source:* *www.eenewseurope.com/en/slideshow-the-other-things-tesla-discovered-invented*

explosives into the funnel of a tornado to break it up (p251, **https://pemag.au/aby0**).

Wirelessly powered aircraft

1934

In a 1934 article (p268, **https://pemag.au/aby0**), Tesla proposed that aircraft would be powered by wirelessly transmitted electricity (Fig.30), among other futuristic proposals.

Telegeodynamics

1934-1941

According to the Tesla Science Foundation, from 1934 to 1941, Tesla worked on what he termed "telegeodynamics". This concerned the transmission of mechanical energy through the Earth via mechanical oscillators. He offered it to various companies, but they were not interested. No practical outcome seems to have arisen from this work.

Teleforce

1934

In 1934, Tesla described a proposed defensive "beam" weapon (also called the "Death-Beam", **https://pemag.au/link/aby7**) he called "Teleforce". The invention was said to be "Powerful Enough to Destroy 10,000 Planes 250 Miles Away".

It comprised an open-ended vacuum tube from which small charged particles of metal or other materials were fired (not subatomic particles). These were accelerated to a high velocity by a large potential difference of perhaps 50MV. For Tesla's description, see: **www.teslaradio.com/pages/teleforce.htm**

Similar experimental weapons have now been developed; see the December 2017 Silicon Chip magazine article on "Rail Guns and Electromagnetic Launchers" (**siliconchip.au/Article/10897**).

Predictions

1934

In *Modern Mechanix and Inventions*, July 1934, Tesla wrote:

We are on the threshold of a gigantic revolution, based on the commercialization of the wireless transmission of power. Motion pictures will be flashed across limitless spaces... The same energy (wireless transmission of power) will drive airplanes and dirigibles from one central base.

In rocket-propelled machines... it will be practicable to attain speeds of nearly a mile a second (3600 m.p.h.) through the rarefied medium above the stratosphere... We will be enabled to illuminate the whole sky at night... Eventually we will flash power in virtually unlimited amounts to planets.

Dynamic theory of gravity

1937

For his 81st birthday, he announced he had developed a "Dynamic Theory of Gravity". He wrote "that it will put an end to idle speculations and false conceptions, as that of curved space", but no further work on this was published.

Tesla passes away

1943

Tesla passed away on the 7th of January 1943, aged 86.

US Government takes Tesla's papers

1943

After Tesla passed away, the US Government came to his room and took many of his papers. While this is the subject of numerous conspiracy theories, bear in mind that this was in the midst of World War 2. The most likely explanation is that they wanted any material related to the proposed Teleforce weapon or anything else that might be useful for the war effort.

If a weapon such as Teleforce had been possible, it would have greatly benefitted the Allied war effort.

Dr John G. Trump (the uncle of Donald Trump) of the US National Defense Research Committee examined Tesla's papers and reported:

[Tesla's] thoughts and efforts during at least the past 15 years were primarily of a speculative, philosophical, and somewhat promotional character often concerned with the production and wireless transmission of power; but did not include new, sound, workable principles or methods for realizing such results.

Zenneck surface waves

much later in 2018

Tesla's dream of global wireless power transmission is not over.

Jonathan Zenneck proposed 'surface waves' in 1907. They represent vertically polarised electromagnetic waves at certain planar boundaries, such as the surface of the Earth. They have been proposed as a means of wireless power transfer.

Power delivery with Zenneck waves was demonstrated in 2020, although only along conducting surfaces and only over a distance of up to 15m – see **https://pemag.au/link/aby8**

We are not suggesting that the idea is technologically or scientifically valid for global power delivery; however, Tesla's dream of wireless power delivery at a large scale remains alive with others.

In 2018, Baylor University in Texas announced a collaboration with Viziv Technologies LLC (**https://pemag.au/link/aby9**). A power transmission tower was built in Texas; see Fig.26.

Unfortunately, Viziv filed for bankruptcy in 2020. See the related article at **https://pemag.au/link/abya** and the videos:

- "Texzon Utilities - Imagine a world without wires" – (**https://youtu.be/7mZErR_ZR3E**)
- "Texzon Zenneck Wave Wireless Power Transmission" – (**https://youtu.be/vQTYaL9jCMo**)
- "Viziv Technologies sends power without wires" – (**https://youtu.be/jK5XUptZDEs**).

Tesla's final decades

Arguably, Tesla's best work was done before about 1900. His final years, until his passing in 1943, involved him living off a small stream of royalties, giving annual press conferences, writing articles about the future of technology and living in seclusion, depression and poverty.

The Life of Nikola Tesla, part two

There was a revival of interest in his work in the 1970s and beyond, some of it from counterculturalists who believed in "free energy". Today, most people know Tesla's name, in part due to Elon Musk's influence. His legacy also inspires other creative scientists and engineers who are prepared to dream and 'push the boundaries'.

Tesla's mistakes and misconceptions

While he was a genius, Tesla evidently made mistakes and had misconceptions. Among these were:

- He did not accept Einstein's theory of curved spacetime
- He did not accept Maxwell's equations
- He believed he had measured faster-than-light speeds
- He did not believe in electrons and thought that atoms were the smallest units of matter
- He believed that the 'aether' transmitted electric currents
- He did not believe the splitting of atoms resulted in the liberation of energy

The aether was once thought to fill the universe and be the medium through which light and gravity were transmitted. The existence of the "luminiferous aether", which transmitted light, was disproven by the Michelson–Morley experiment in 1887, and subsequent experiments.

Some of these misconceptions are remarkable, given his highly successful early work with electricity and magnetism.

Tesla also said of nuclear energy, "The idea of atomic energy is illusionary but it has taken a powerful hold on the mind and there are still some who believe it to be realizable".

In an article in the *Electrical Experimenter* of February 1919, he also wrote that the moon does not rotate on its axis (p14 of **https://pemag.au/link/abyd**). However, it was known at the time that it did. In fact, it rotates in synchrony with the Earth, so we always see the same side of the moon.

World Wireless System flaws

It is certainly possible to transmit power wirelessly; we see it every day in things like mobile phone wireless chargers. They are based on 'near field' effects that occur close to the transmitting device.

In the near field, the electric and magnetic field components of an electromagnetic wave can exist independently of each other, while in the 'far field', the electric and magnetic fields are perpendicular to each other. Far-field charging techniques are also available, but they require strongly focused beams such as lasers or microwaves.

What Tesla demonstrated as wireless power transmission involved either

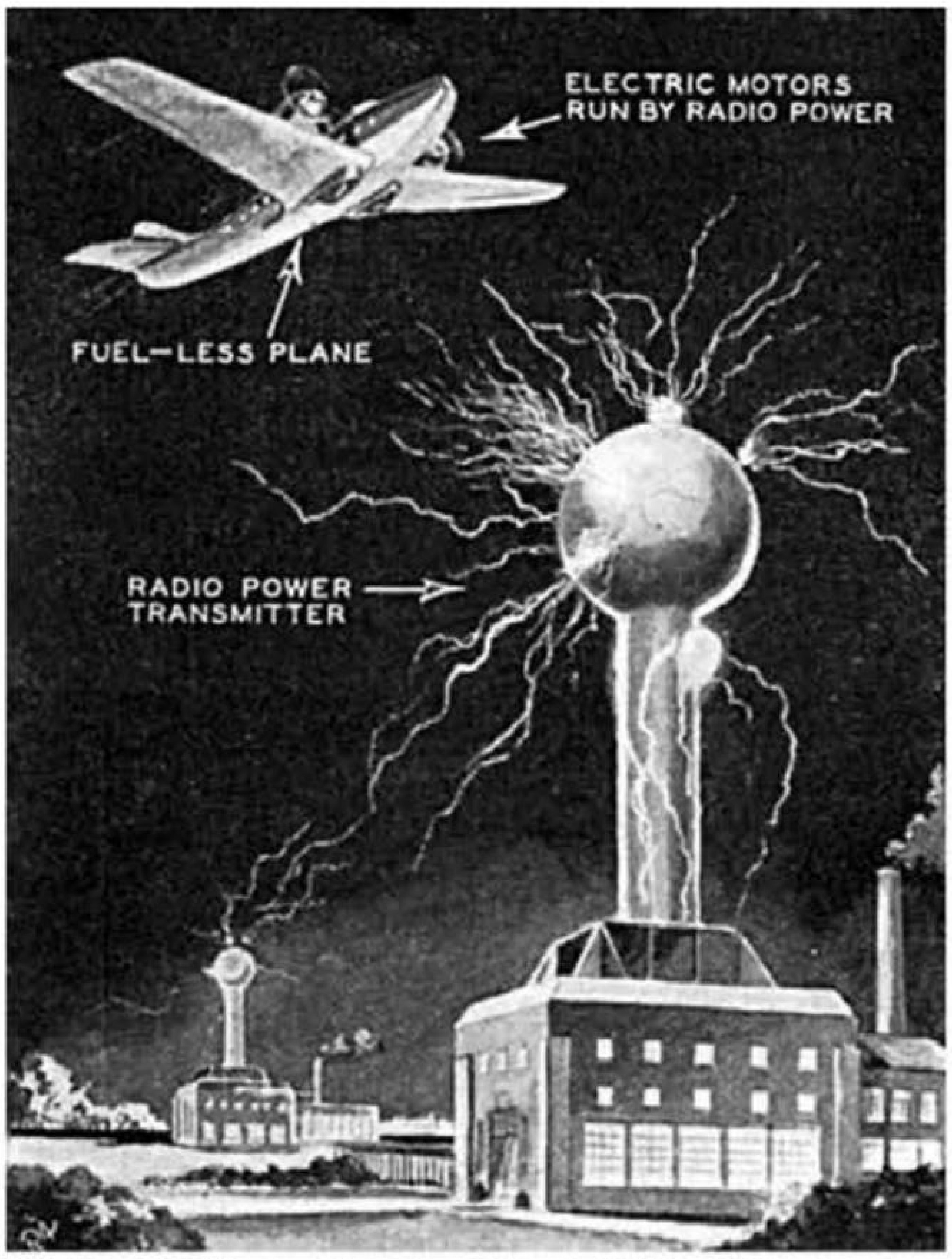


Fig.30: an illustration from the July 1934 Modern Mechanix and Inventions magazine of a proposed electric aircraft, to be powered wirelessly.

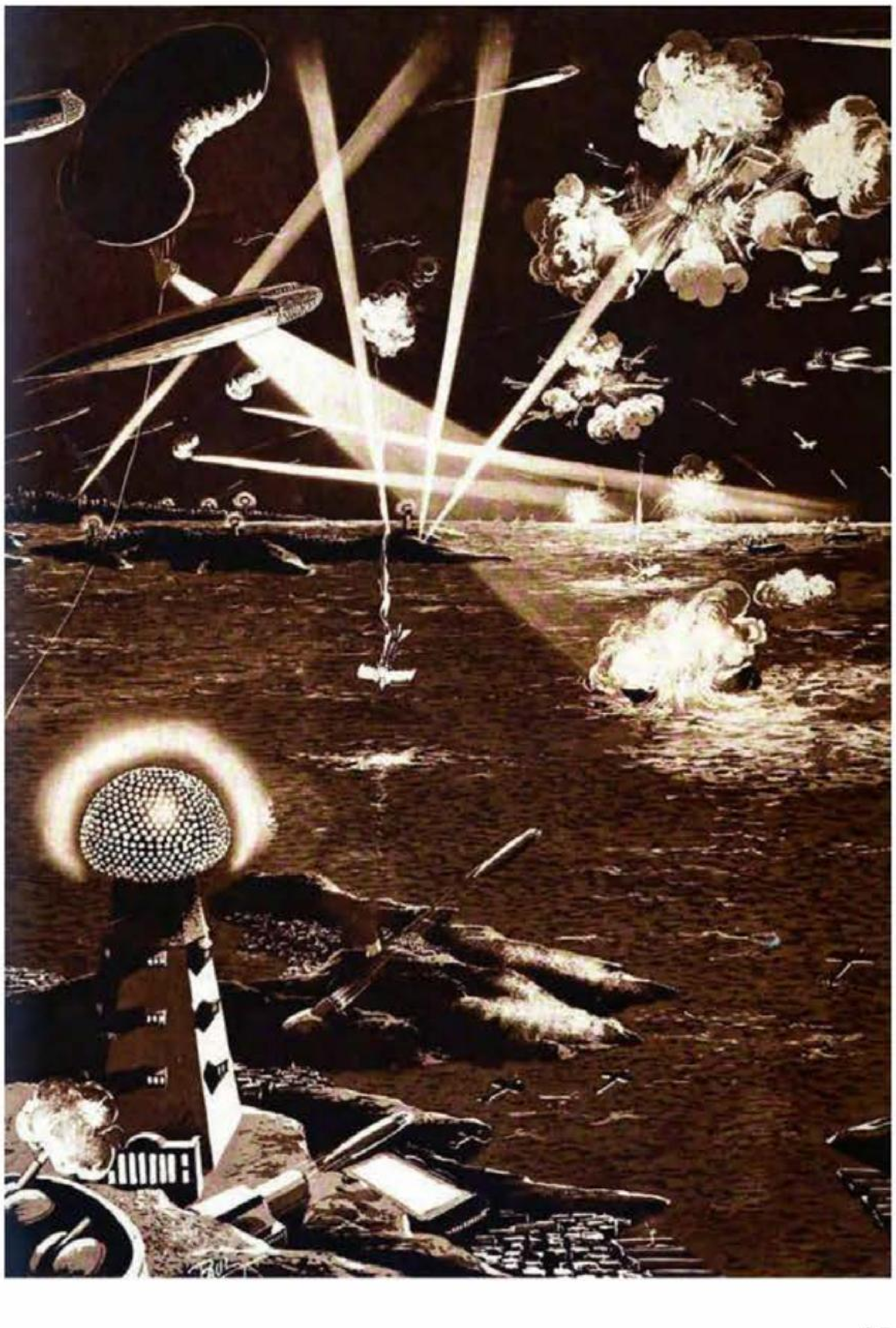


Fig.31: the future of warfare, as envisaged by Tesla and illustrated by Frank R. Paul in 1922. This image ties together some of Tesla's ideas, such as wireless power transmission, radio and teleautomatons (remotely operated vehicles). Few people would be hurt in this war, as it would be mostly between remote-controlled machines. ***Source: https://w.wiki/AbV4***

capacitive coupling (such as when a fluorescent tube illuminates near a high-voltage power line) or inductive coupling (like in an air-cored transformer). These are near-field phenomena and do not work at extended distances beyond a few tens of metres and certainly not worldwide.

Besides, the energy of electromagnetic waves decreases with the distance from the antenna.

Tesla also incorrectly believed that the entire Earth could be made to electrically resonate in the manner of an LC circuit. He thought that, by injecting current into the Earth at its resonant frequency from a grounded Tesla coil with a capacitance, standing waves could be established around the Earth that could be received at their nodal points anywhere on Earth with an antenna tuned to resonance.

Another idea Tesla had was to hoist both transmitting and receiving power antennas high up into the atmosphere on balloons, to about 9100m, where he thought the rarefied air would be sufficiently electrically conductive to transmit electric power, with the Earth being the return circuit.

That idea would not be practical; the ionosphere (not discovered until 1924), where the atmosphere does become electrically conductive, starts about 48km above the surface.

Tesla and alternating current

Contrary to popular belief, Tesla did not invent the concept of AC electricity. The first AC generator was invented in 1832 by Hippolyte Pixii, as mentioned in our article on the History of Electronics (February 2025, p55). However, André-Marie Ampère convinced him to convert it to pulsed DC.

According to the book The Electric Light from 1884 (p238, https://pemag.au/link/abye), around 1856, due to frustration with failed commutators on a generator, they were dispensed with, resulting in the successful use of AC for lighting, such as arc lights. However, Tesla did invent many successful AC machines.

War of the currents

The war of the currents lasted from the late 1880s to the early 1890s and basically concerned which of the two electrical systems would dominate large-scale electricity distribution. These were AC, represented by George Westinghouse (and Tesla), and DC, represented by Thomas Edison.

AC was ideal for long-distance distribution because, at high voltages, it had low transmission losses and it was easy to change the voltage for use by the consumer with a low-cost, reliable transformer. DC systems had high losses at low voltages and would have required vast numbers of local power stations since DC voltage conversion was not practical.

Edison promoted the safety of DC compared to the dangers of AC. Edison and Westinghouse's other rival, Thomson-Houston Electric Company, even colluded to ensure the first electric chair was powered by a Westinghouse AC generator to 'prove' how dangerous AC was.

In 1893, Westinghouse won the contract for lighting at the Chicago World Fair, at which Tesla's inventions were demonstrated, and won most of the contract for the Niagara Falls hydro-electric project, at which Tesla's generators were used. This ensured the future of AC.

During the war of the currents, and even afterwards, some residences in New York had both DC and AC outlets, which looked the same!

The last DC utility service in New York was shut down in 2007, see: www.edisontechcenter.org/NYC.html

Tesla and radio

Tesla had studied and was aware of Hertzian radio waves. However, he believed Hertz's theories were incorrect and that Hertzian waves were not suitable for anything but short-range communications, such as under 2km. He also thought they behaved like light and would go straight into space rather than travel long distances on Earth.

Tesla was more interested in wireless long-distance electricity transmission than in communications. However, in 1893, he noted that his proposed wireless electricity transmission system could also be used for communications.

Tesla also incorrectly believed, as some others did at the time, that radio behaved much like the familiar telegraph system and that a return circuit was required, with radio waves travelling through the air and a return path of current through the Earth.

While the Earth plays an important role in a radio system by providing a reference potential and allowing a small amount of current to flow through it, radio signals do not 'return' via that path.

He incorrectly believed that radio waves could travel losslessly through the Earth. Tesla also had an idea of producing non-Hertzian "longitudinal electromagnetic waves" in the manner of sound waves, which he called "electromagnetic thrusts". Radio waves are, in fact, transverse.

Tesla's "lost files"

There are many conspiracy theories related to Tesla's documents, which the US Government took after his passing. After they found nothing of practical use for the war effort (such as the "death ray"), the papers were released to Tesla's relative, Sava Kosanović.

He took them, along with Tesla's entire estate (packed into 80 trunks) to Belgrade, Serbia in 1952, and they now reside in the Nikola Tesla Museum in Belgrade. PE

Links and References

- Nikola Tesla and the Planetary Radio Signals: **https://radiojove.gsfc.nasa.gov/education/educationalcd/Books/Tesla.pdf** (K. L. Corum & J. F. Corum, 2003).
- Tesla's autobiography from 1919: **www.tfcbooks.com/tesla/my_inventions.pdf**
- Plans to make your own Tesla turbine: **www.instructables.com/Tesla-Turbine**
- The Nikola Tesla Museum in Belgrade: **https://tesla-museum.org/en/home/**
- A 301-page collection of some of Tesla's writings, called "Tesla Said", is described as "the most comprehensive single volume of Tesla's writings": **https://archive.org/details/nikolateslajohnt.ratzlaffteslasaid**
- Tesla: Inventor of the Electrical Age, W. Bernard Carlson, Princeton University Press (2015).
- The Tesla Memorial Society of New York: **www.teslasociety.com**
- The Tesla Science Center at Wardendclyffe: **https://teslasciencecenter.org**
- The Tesla Collection, a comprehensive compilation of newspaper and periodical material: **https://teslacollection.com**

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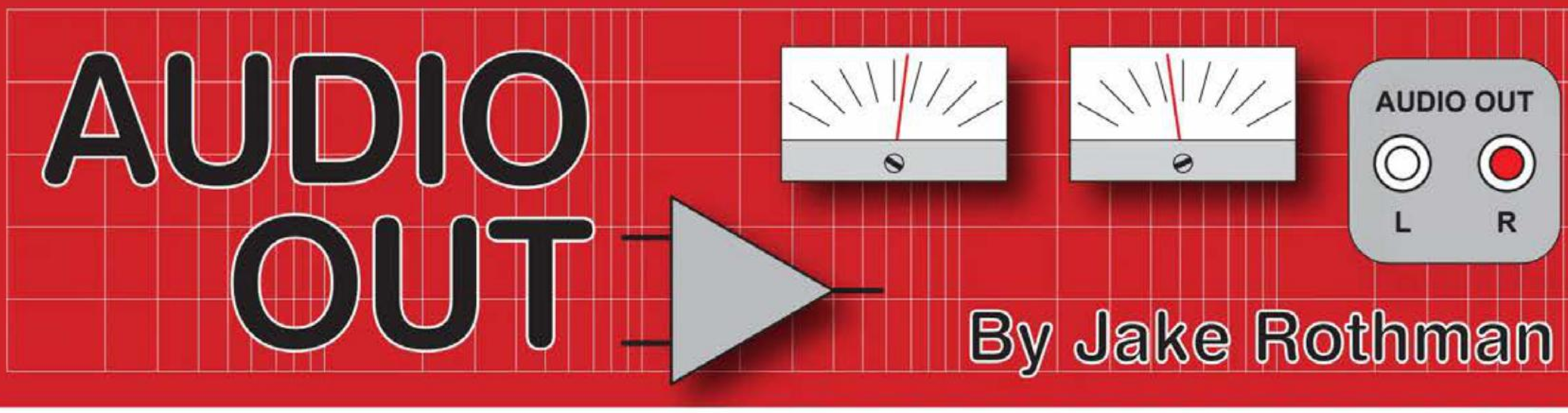


AUDIO OUT

By Jake Rothman

The Transmanium fuzz box, part 1

Guitar electronics is a fringe activity, more of an art than a science. It's all about musical feel and the creative neural feedback loop between the player and the speaker. Everything you have learned about in Hi-Fi audio design is almost irrelevant, if not despised, among the guitar fraternity.

Present an Audio Precision curve at a guitar pedal convention, and you would likely to be booed off. Because of this attitude, fundamental electronic engineering errors occur and breakdowns are common. But there is a good side; a competent electronic engineer can diverge from traditional design and do something experimental.

Impedance

Impedance is one basic electronics parameter that does concern guitarists. Electric guitars came about in the age of valves, which are high-impedance devices; in fact, they act a lot like Mosfets.

Consequently, guitars reflect this, using electromagnetic pickups typically wound with 5000 turns of 46 SWG (0.06mm diameter) wire, having an inductance of around 5H. You may recall this being discussed in the Electric & Bass Guitar Pickguards project article last month.

To achieve a sufficient signal voltage level, and to prevent the inductance from causing high-frequency signal loss, the guitar pickups need to be loaded with an impedance of 250kΩ or greater, easily provided by a valve input stage. This goes against modern audio design, with its low-noise op amps surrounded by low-value resistors for minimum noise.

I've tried and failed to convince guitarists they should use low-impedance pickups with balanced XLR outputs. It's just impossible to change 80 years of tradition. If you feed an electric guitar into a typical op amp circuit, with say 10kΩ input impedance, it sounds horrible: quiet, dull and hissy. So, 1MΩ input impedance it is, with unbalanced quarter-inch (6.35mm) jack plugs.

Negative feedback, no thanks!

Another thing guitar electronics people have against modern audio design is its distortion curve, a result of high negative feedback and analog-to-digital conversion. This technology exhibits a consistently low distortion level as the level increases, ending with sudden hard clipping.

For a good human interactive playing response, this is not acceptable. What is needed is soft clipping and a gradual increase in distortion, as is exhibited by acoustic instruments, such as a piano soundboard. This of course explains the preference of guitarists for valve amplifiers feeding stiff light-weight paper cone loudspeakers.

It is said the first fuzz was created by a damaged (possibly deliberately ripped) speaker cone. Of course, every musically minded kid would stuff newspapers down the piano strings to get buzzy distortion or 'fuzz'. I remember annoying my parents with it when around eight years old, possibly my first attempt at waveform manipulation!

Fuzzy logic

This high distortion characteristic loved by guitarists makes most Hi-Fi and studio engineers shudder, but since the 1960s, guitarists such as Jimi Hendrix took it to a whole new level. They made the distortion part of the musical instrument, with a distortion circuit called a fuzz box, taking the THD well over 300%.

This is possible, where the sum of the harmonics is greater than the fundamental. An AP curve would be useless to characterise a fuzz box, just flat-lining at 100%. More useful are spectral analysis plots at different levels, but mathematics and the science of human perception mean little to guitarists, unless it's a volume control that goes to 11.

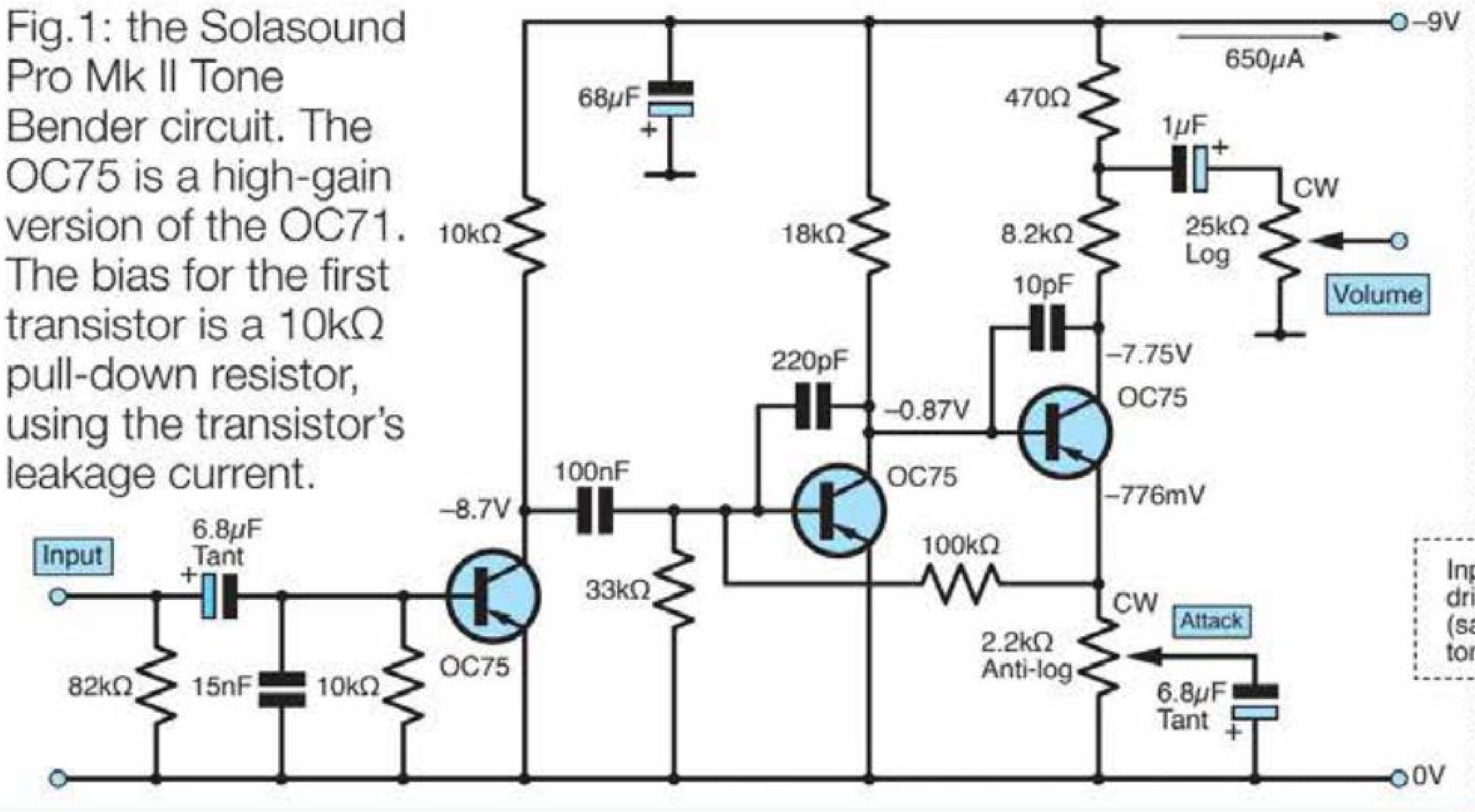


Fig.1: the Solasound Pro Mk II Tone Bender circuit. The OC75 is a high-gain version of the OC71. The bias for the first transistor is a 10kΩ pull-down resistor, using the transistor's leakage current.

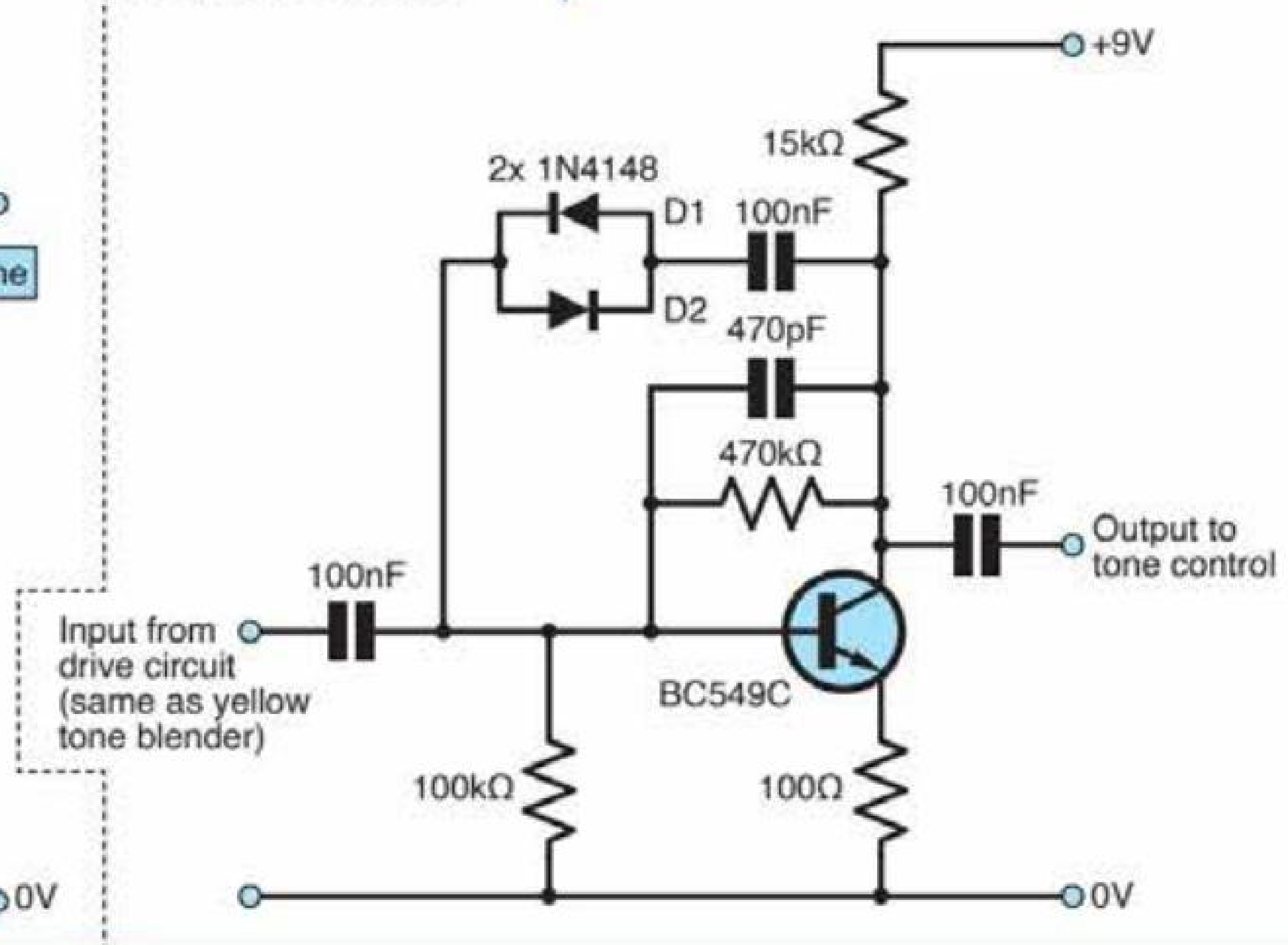


Fig.2: the final clipping stage on the Silver Tone Bender.

INPUT
OUTPUT
VOLUME
FILTER
Marshall
Supa Fuzz

Photo 1: the Pro Mk II Tone Bender, the first successful British fuzz box (still in production today!). This rebadged version was made for Marshall.

[Editor's note: in audio reproduction, distortion is undesirable because the output signal is not as the artist intended, while in music creation, it is a tool to achieve a desired effect.]

Fuzz circuits and transistors

The first commercial fuzzbox was an over-driven three transistor amplifier, the Gibson Maestro FZ-1 Fuzz-Tone, using RCA germanium 2N270s running off 3V. This hit the market in 1962. A very similar circuit (Fig.1) using Mullard's high-gain OC75 was introduced in the UK by Gary Hurst, the Color/Solasound Tone Bender Mk II in 1966, shown in Photos 1 & 2.

It ran on a 9V PP4 battery giving longer sustain. This three-transistor format still forms the basis for many designs, including the one in this article. There were cheaper two-transistor topologies, such as the Fuzz Face, using Newmarket NKT275s, but there were excessive gain variations between units.

The sound of fuzz changed when silicon transistors replaced the original germanium devices. It became brighter, more consistent and less temperature-sensitive. The Silver Tone Bender, designed by Dick Denny, used three silicon BC169 transistors, a BC109 die in a then-new cheap epoxy package.

The clipping stage used two IN4148 diodes AC-coupled in a feedback loop between the base and collector, giving a clean, consistent buzz. The pedal is shown in Photos 3 & 4, while the clipping part of its circuit is shown in Fig.2. By the way, Dick Denny was most famous in the guitar world for designing the Vox AC30 valve amplifier, many variants of which are still built today.

Positive ground

Nearly all germanium transistors are PNP types, meaning some people preferred to use a positive ground with a negative supply rail. If the fuzzbox has its own battery, this is not a problem, but if it's powered from a common power supply with other negative-ground devices, the power rail is shorted out.

When guitarists assemble pedalboards with multiple effects (Photo 5), this often catches them out. If one can obtain germanium NPN transistors, this problem can be avoided. My favourite device is the Philips OC140 used in the Yellow TB, but it

INSTRUMENT
TONE-BENDER
AMPLIFIER
SOLA SOUND LONDON ENGLAND
VOLUME
TONE
FUZZ
PRE-SET
BUTTON
HIT IT!

Photo 3: the Tone Bender is the classic silicon transistor fuzz box. I have built many!

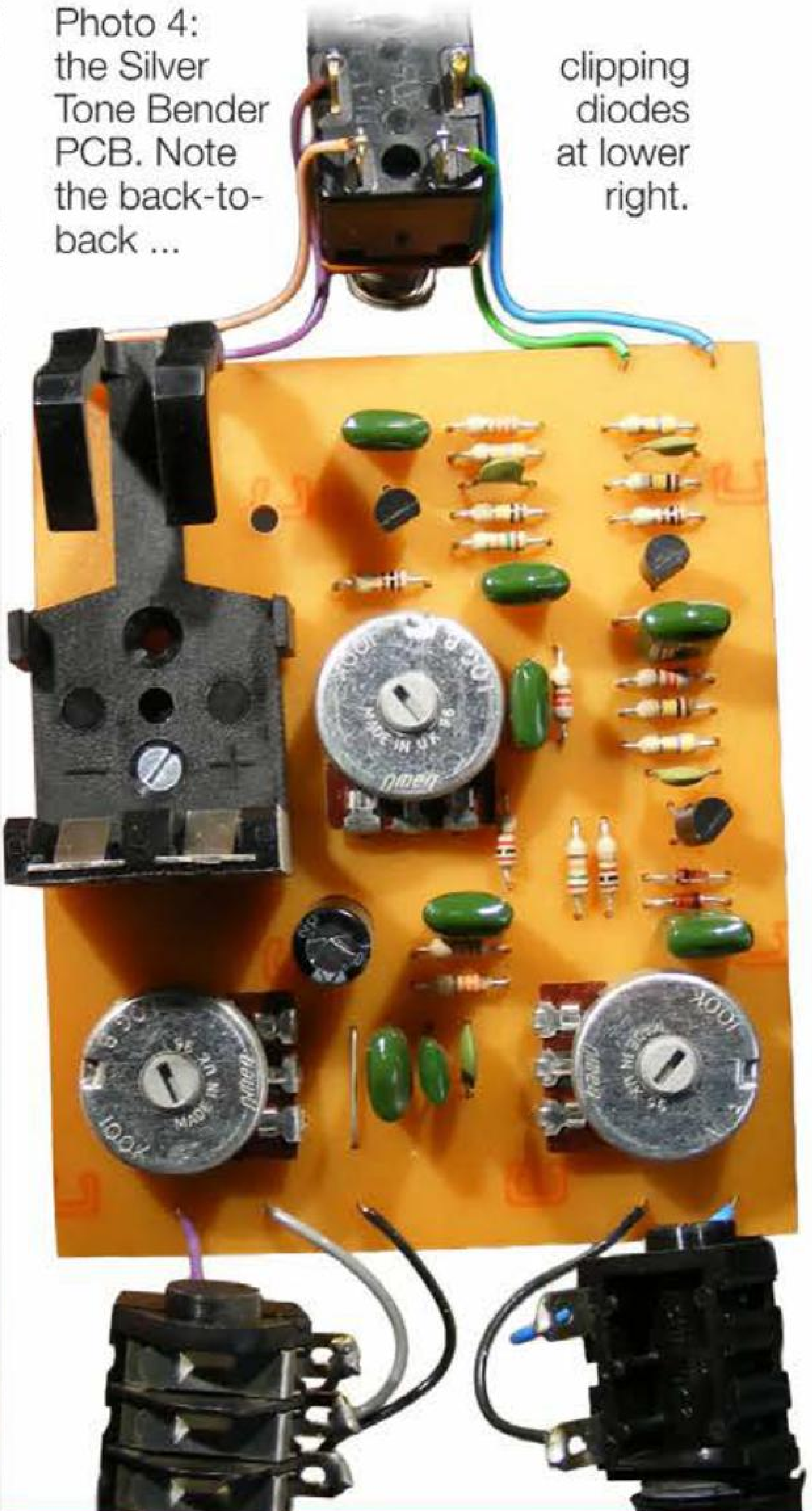


Photo 4: the Silver Tone Bender PCB. Note the back-to-back ... clipping diodes at lower right.

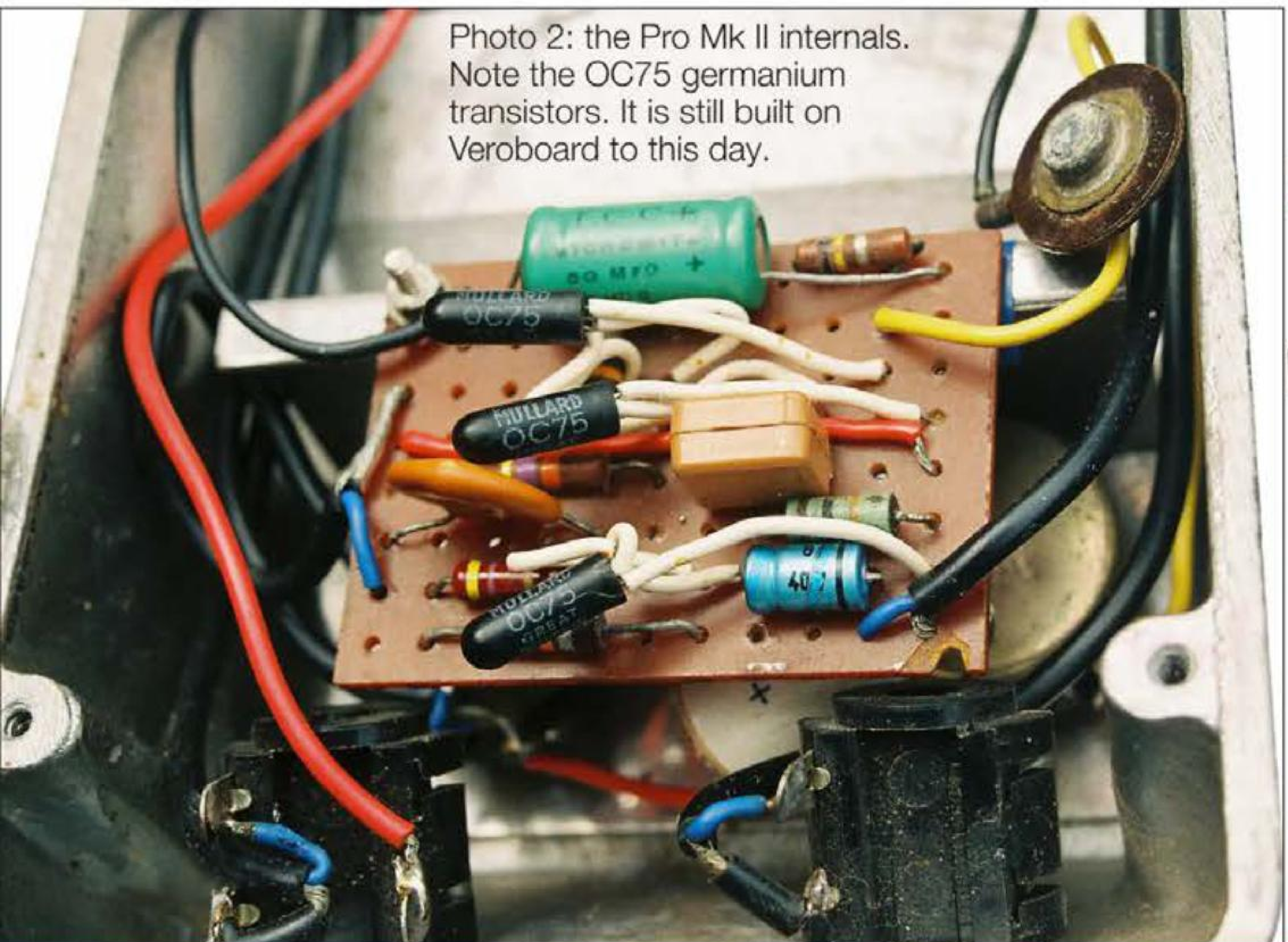


Photo 2: the Pro Mk II internals. Note the OC75 germanium transistors. It is still built on Veroboard to this day.

Photo 5: a guitarist's pedal board. Usually, all the effects are fed off a single power supply; this is a recipe for hum loops and other problems. Source: Mike Grindle.

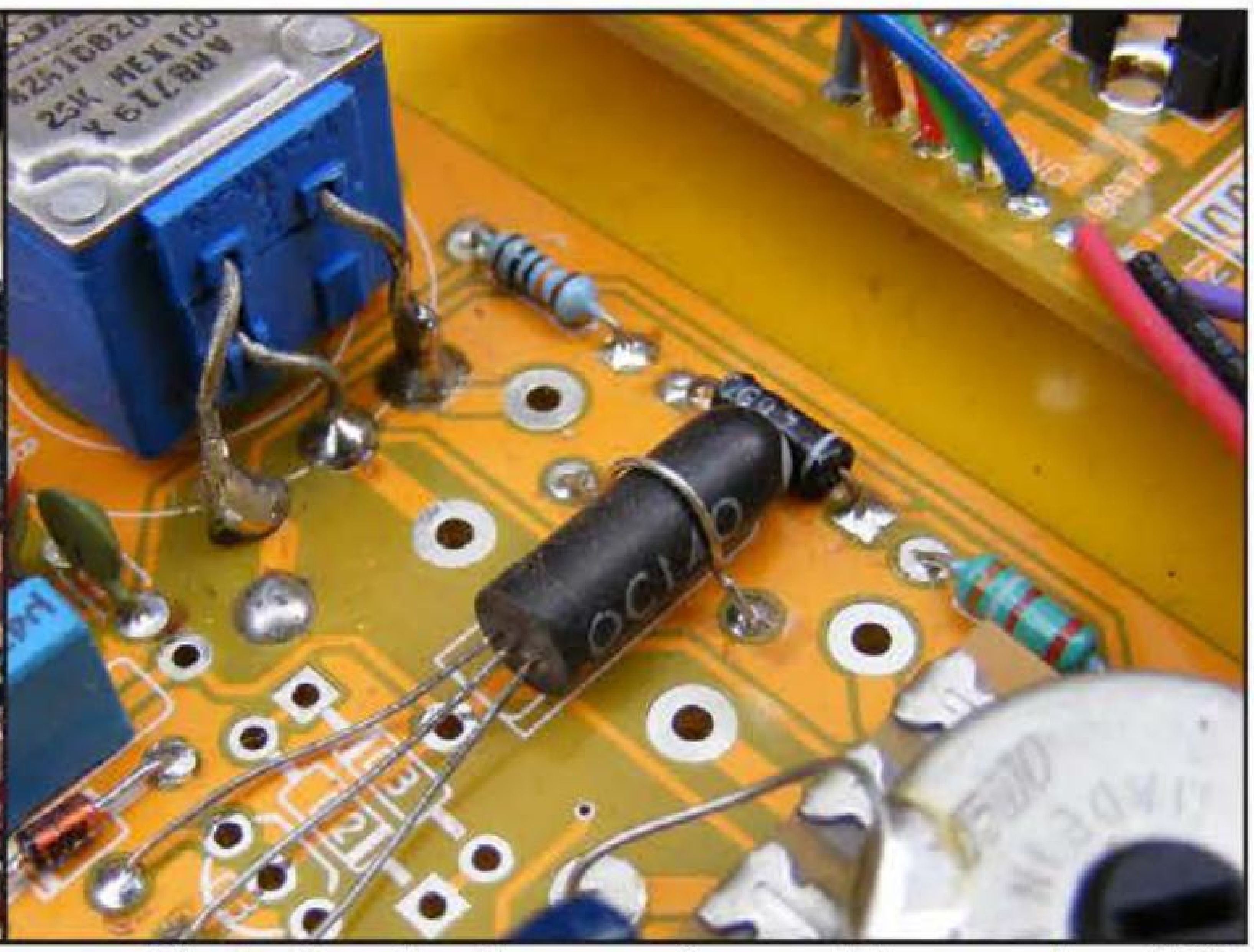


Photo 7: notice the use of a special germanium NPN OC140 along with black anti-leakage diode CG92 in the Tone Bender.

is rare and expensive. Colorsound's source came from a Malaysian RAF spares store for V bombers via Cyclops Electronics of York.

Junk box junctions

I suspect that most older audio constructors have at least one old germanium transistor in their junk box, and it is most likely to be a PNP type, such as the audio classic OC71 or AC126. Old radio-frequency types can also be used, such as the alloy-junction OC44, but they sound too bright. Alloy-diffused RF types, such as the AF117, are no use because of their high noise level.

Interestingly, Soviet germanium transistors are available (Photo 6) and they have low leakage. They carried on making them a lot longer than the West, so maybe they were developed further.

Photo 6: this Soviet germanium transistor had zero leakage current according to the Peak analyser.

Circuit structure

Fuzz circuits have always used common-emitter stages for maximum voltage gain, usually with a drive control in the middle, a passive tone control on the output and a master volume on the end. There is also a foot switch controlled hard bypass, which is important since the musician won't necessarily want the fuzz effect all the time.

This design follows the typical block diagram shown in Fig.3. Some fuzz circuits have a mix control between clean and clipped signals. I don't like this approach because it sounds disintegrated, like two separate guitars. Mix controls are useful in bass fuzz boxes to allow the fundamental through.

I decided to use silicon transistors for the first two stages to get high gain, with the final clipping stage being germanium. I used this approach when designing the Colorsound Yellow Tone Bender for Macari's (see Photos 7 & 8 and **https://pemag.au/link/ac8m**). I found that this topology gives the best of both worlds.

The input and driver stages were the same as in the Silver Tone Bender, with the BC169s replaced by the modern version, the BC549. The circuit is shown in Fig.4.

The circuit for the Transmanium is shown in Fig.5. Its input stage is a JFET common-source amplifier

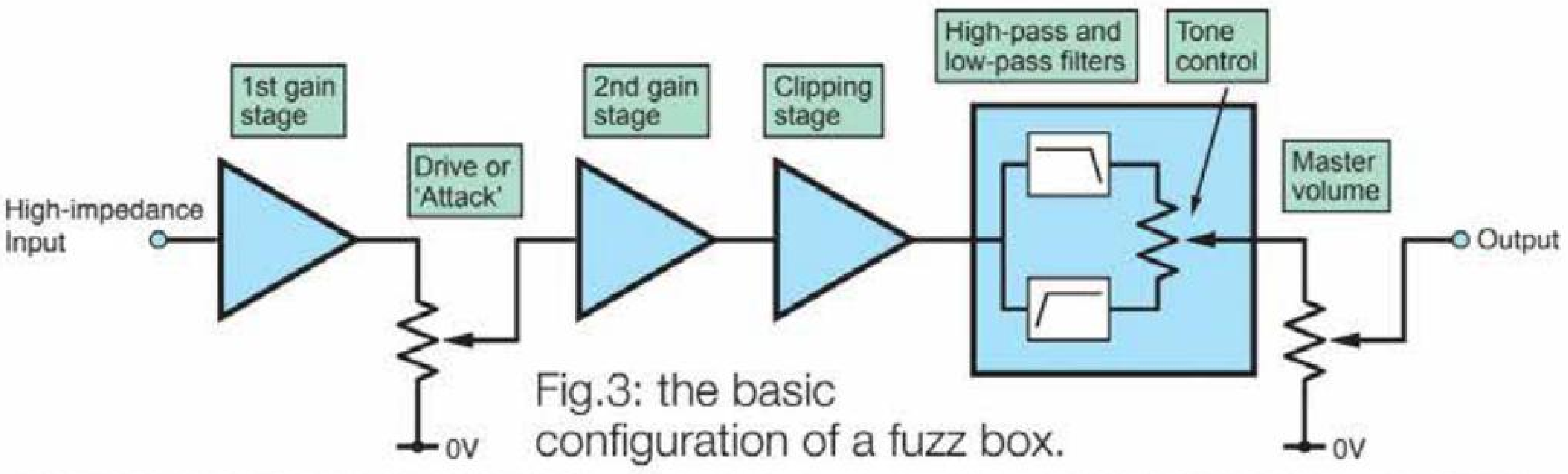

1st gain stage
Drive or 'Attack'
2nd gain stage
Clipping stage
High-pass and low-pass filters
Tone control
Master volume
High-impedance Input
Output
0V
0V

Fig.3: the basic configuration of a fuzz box.

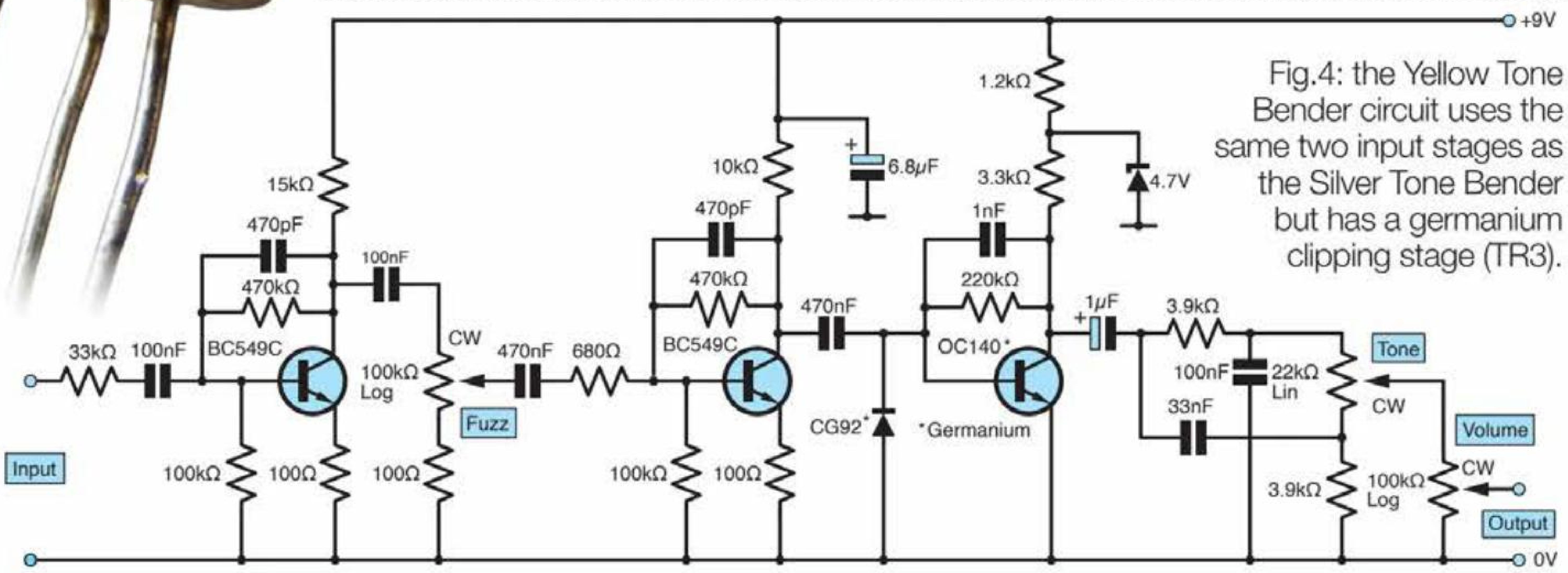
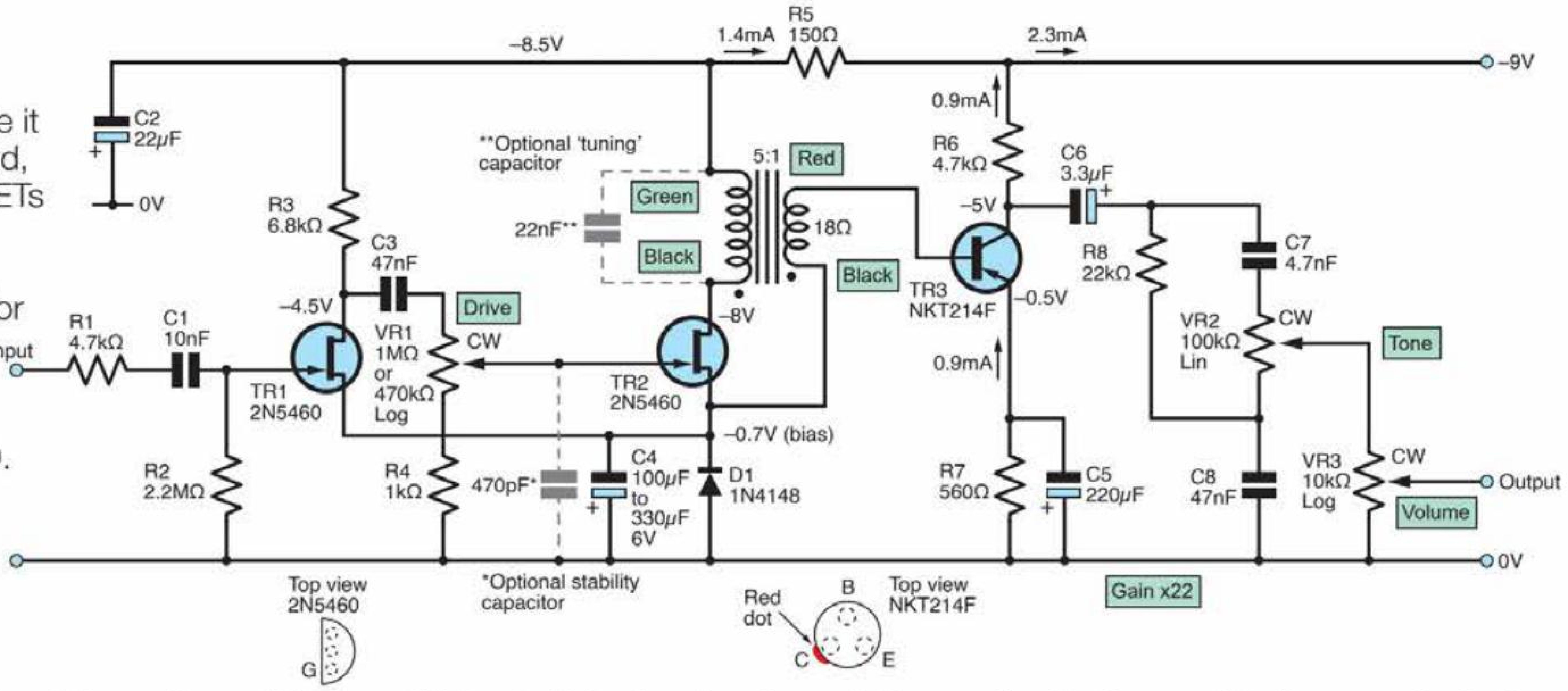

+9V
0V
Input
Output
15kΩ
470pF
470kΩ
100nF
33kΩ
100nF
BC549C
100kΩ
100Ω
CW
100kΩ Log
Fuzz
100Ω
470nF
680Ω
10kΩ
6.8μF
470pF
470kΩ
BC549C
100kΩ
100Ω
470nF
CG92*
1.2kΩ
3.3kΩ
4.7V
1nF
220kΩ
OC140*
*Germanium
1μF
3.9kΩ
100nF
22kΩ Lin
Tone
CW
33nF
3.9kΩ
100kΩ Log
Volume
CW

Fig.4: the Yellow Tone Bender circuit uses the same two input stages as the Silver Tone Bender but has a germanium clipping stage (TR3).

Fig.5: the Transmanium circuit. To make it negative ground, change the JFETs to N-channel 2N5457s and output transistor TR3 to a germanium NPN type, like the OC139. The diode and all electrolytics must also be reversed.


–8.5V
R5
1.4mA 150Ω
2.3mA
–9V
C2
22μF
0V
**Optional 'tuning' capacitor
5:1
Red
Green
22nF**
Black
18Ω
Black
0.9mA
R6
4.7kΩ
C6
3.3μF
–5V
R8
22kΩ
C7
4.7nF
R3
6.8kΩ
C3
47nF
–4.5V
Drive
R1
4.7kΩ
C1
10nF
Input
VR1
1MΩ
or
470kΩ
Log
CW
–8V
TR3
NKT214F
–0.5V
0.9mA
VR2
100kΩ
Lin
CW
Tone
TR1
2N5460
TR2
2N5460
–0.7V (bias)
R2
2.2MΩ
R4
1kΩ
470pF*
C4
100μF
to
330μF
6V
D1
1N4148
R7
560Ω
C5
220μF
C8
47nF
VR3
10kΩ
Log
CW
Output
Volume
0V
Top view
2N5460
G
*Optional stability capacitor
Red dot
B
C
E
Top view
NKT214F
Gain x22

to get a high input impedance. The second stage is practically the same. Its high input impedance minimises input stage loading by allowing a high-value pot to be used for the drive control. The final stage is an overdriven germanium transistor, which gives the characteristic sound.

Leakage current

A major problem with germanium transistors is base leakage current, which can cause the transistor to switch on excessively, even when unbiased. It is especially bad with old 'junk box' devices, so I designed this circuit to cope with it. In the Pro Mk II first stage, there was no bias voltage at all. Leakage current alone was sufficient at the low levels, and the resulting distortion was a good thing.

With the Yellow Tone Bender, I used a reverse-biased germanium diode (D1) across the base-emitter junction to cancel out the increase in leakage current with temperature. A modern, more effective way would be to use an op amp in a servo loop built around the germanium device to hold its output at the right point.

Then again, if I did that, conservative guitarists would be up in arms.

Biased transformer coupling

I decided to go back to a 1960s way of minimising leakage current effects: using a transformer to couple the input. In this way, the source resistance of the bias network can be reduced from, say, 10kΩ to around 50Ω, so the leakage current flowing through it generates little voltage to bias the transistor on.

The bias voltage is fed in series with the bottom of the transformer winding, so there is minimal loading, feeding all the power from the preceding stage into the output stage, TR3.

The bias voltage is created by a forward-biased semiconductor, so it provides temperature compensation at the same time. So long as 0.7V bias is not too high, a silicon diode (D1) can be used rather than an expensive germanium diode. The voltage vs temperature relationship is a semiconductor physics law, and is the same for both types. It's just the forward voltages that are different between them.

AMPLIFIER
TONE-BENDER
SOLA SOUND
LONDON · ENGLAND
INSTRUMENT
BASS
TREBLE
VOLUME
FUZZ
BUTTON
PRE-SET
HIT IT!

Photo 8: the 1970s Yellow Tone Bender has a lovely, grungy sound.

Bias shift

There are some more advantages of transformer coupling, such as no input coupling capacitor being required. Such a capacitor can charge up on loud tone bursts, causing a bias shift, switching the transistor off briefly. This effect sounds horrendous, punching holes in the sound.

This happens because the DC resistance path is unequal in the positive and negative directions. The transistor's base-emitter junction is a diode after all.

Another way around this problem is to place a reverse-biased diode across the base-emitter junction of the transistor, equalising the paths. This was an additional function of the germanium diode in the Yellow Tone Bender. Interestingly, a bit of a bias shift in the right direction can enhance the sound, causing a form of pulse-width modulation.

Finally, transformer coupling provides a high-impedance AC load for the drain of JFET TR2, while having a low DC resistance. This doubles the effective supply voltage, the drain being at around 8.5V rather than 4.5V. This boosts the gain of the relatively low-gain JFET.

The transformer has to be a step-down device, typically with a 5:1 turns ratio, to avoid the low input impedance of TR3 loading TR2, reducing the gain. Obviously, we don't need an expensive Hi-Fi unit here. Any interstage or driver transformer used in cheap transistor radios will do the job.

Phasing

All the stages in the fuzz box are inverting, which means the system is inverting overall. The transformer wires on either winding can be flipped to change the overall phase. If the transformer is wired to be inverting, the whole system will become non-inverting.

Note that in the circuit diagram, the phasing of the transformer is shown by dots. Current flowing into the dotted end on one side will flow out of the dotted end on the other side and vice versa.

Magic?

Here's where some strange things can happen. I tried putting a phase polarity switch on the transformer, and the sound was better in one position. Mike Grindle, who can actually play guitar (unlike me) noticed the difference much more and preferred the transformer in non-inverting mode, as shown in the diagram.

The sound could be described as "meatier", with subjectively more low frequencies. The engineer in me was displeased, since I think any audio circuit should be non-inverting. Inverting equipment can cause cancellations when combined in various audio pathways in the studio.

I've had this distortion phase effect before, and it is usually caused by curvature cancellation in cascaded inverting stages. (Yes, it is possible to add another stage and get less distortion).

Another cause is an asymmetrical clipping action. I thought it best to stick with the configuration that gave the best sound, ie, inverting overall.

I've found most guitar pedals to be inverting. All the Colorsound Tone Benders are, apart from the Supa Tone Bender, which has an extra stage, and no one complains.

Power polarity flip

Transformer coupling also allows a PNP transistor to be biased 'upside down', as shown in Fig.6, thus enabling a conventional positive power rail to be used. I tried this on a breadboard, and there was instability, possibly due to there being two ground reference points. I'm going to continue pursuing this, though, as I have 1000 PNP NKT214s in stock.

I/P
O/P
TONE
VOL
GAIN
HARDWIRED
HI WATT STYLE
2 x FET 1x TRANSFORMER 1x GERMANIUM
TRANSMANIUM
PROTOTYPE VOX
ESCORT TONE CONTROL

Photo 9: the prototype Transmanium germanium fuzz box. Source: Mike Grindle.

PROTO - FETMANIUM
2x FET
TRANSFORMER
COUPLED TO
GERMANIUM

Photo 10: inside the fuzz box, it's 'hard wired', so very easy to modify. Source: Mike Grindle.

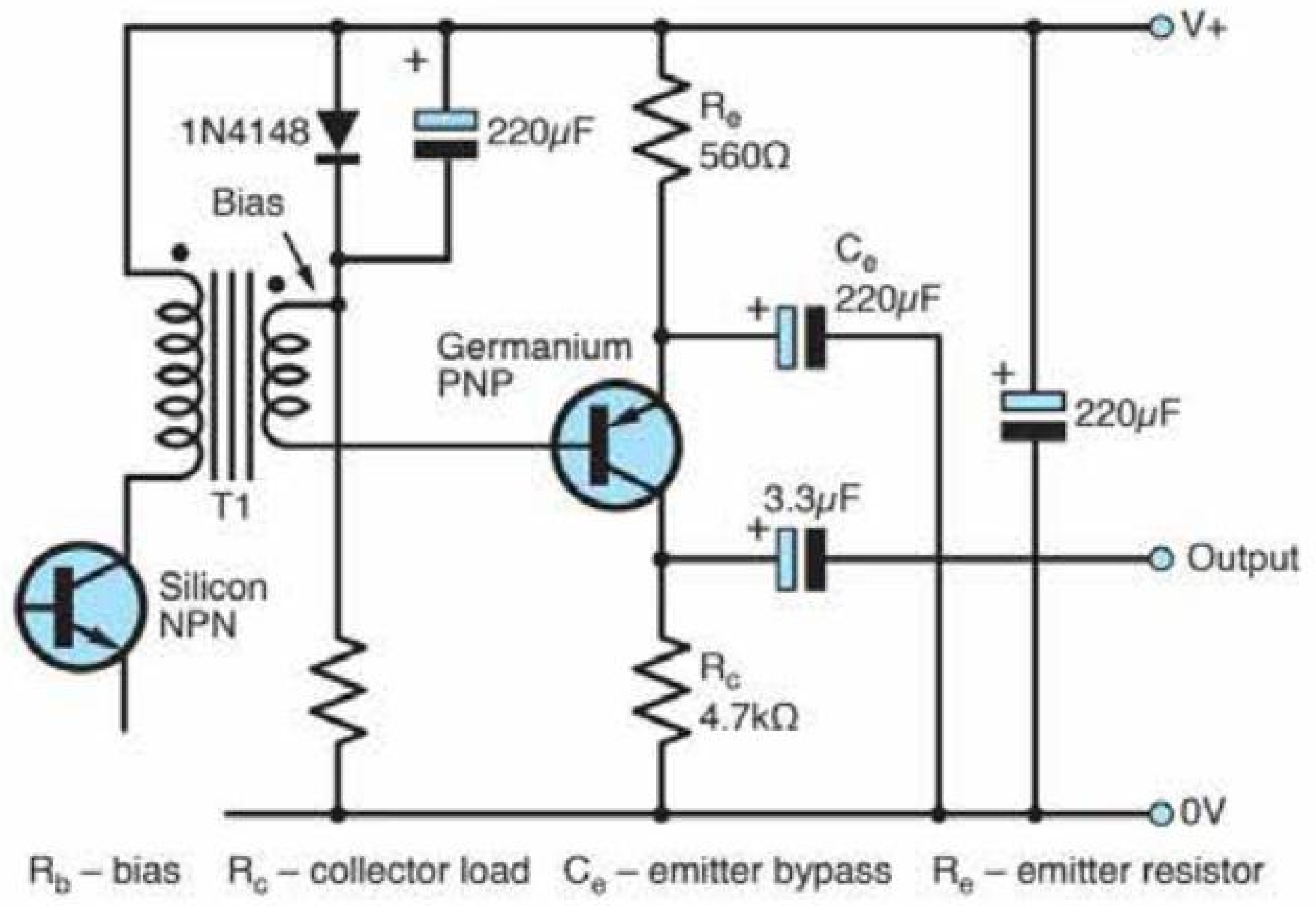

V+
1N4148
220µF
+
Rₑ
560Ω
Bias
Cₑ
220µF
Germanium
PNP
220µF
T1
3.3µF
Output
Silicon
NPN
R꜀
4.7kΩ
0V
R_b – bias
R_c – collector load
C_e – emitter bypass
R_e – emitter resistor

Fig.6: a developmental circuit for using a PNP transistor 'upside down' to obtain a negative ground.

Filtering

Low-pass filtering of the input signal reduces harsh intermodulation products. High-pass filtering of the output removes the low-frequency beats resulting from intermodulation, and is usually accomplished by using low-value coupling capacitors.

On some bipolar transistor fuzz boxes, such as the Silver Tone Bender, the low-pass filtering is done by making the input impedance rather low, and wiring capacitors between the base and collector of each transistor. Its 70kΩ input impedance rolls off the HF from the pickup above about 3kHz. It also renders the guitar's tone control ineffective, which is disconcerting.

In the circuit here, we can wire a capacitor across the interstage

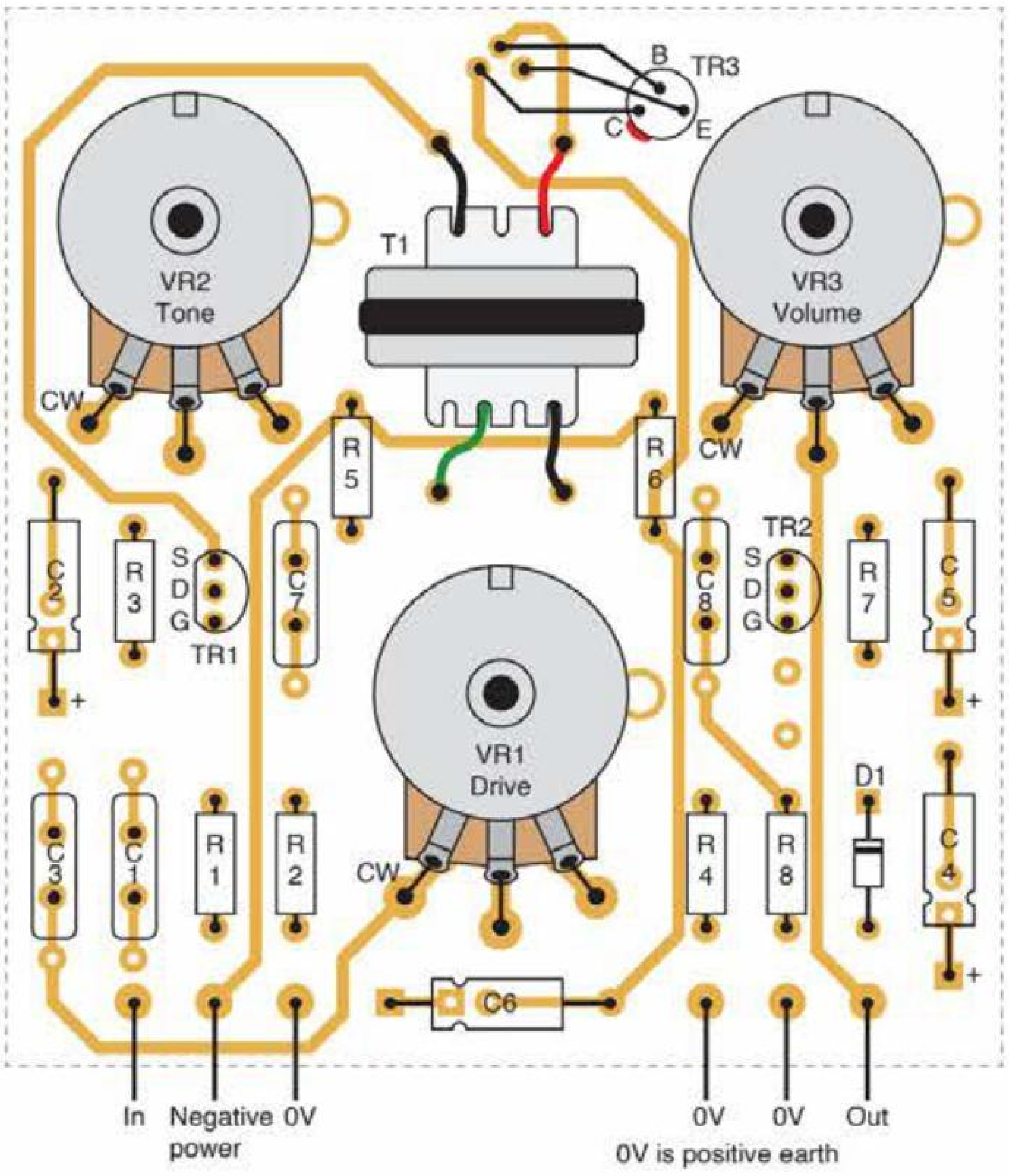

B
TR3
C
E
T1
VR2
Tone
VR3
Volume
CW
CW
CW
R5
R6
C2
R3
S
D
G
TR1
C7
C8
TR2
S
D
G
R7
C5
+
+
VR1
Drive
D1
C3
C1
R1
R2
R4
R8
C4
+
C6
In
Negative power
0V
0V
0V
Out
0V is positive earth

Fig.7: the PCB overlay for the Transmanium. There is provision for the optional stability capacitor just beneath TR2.

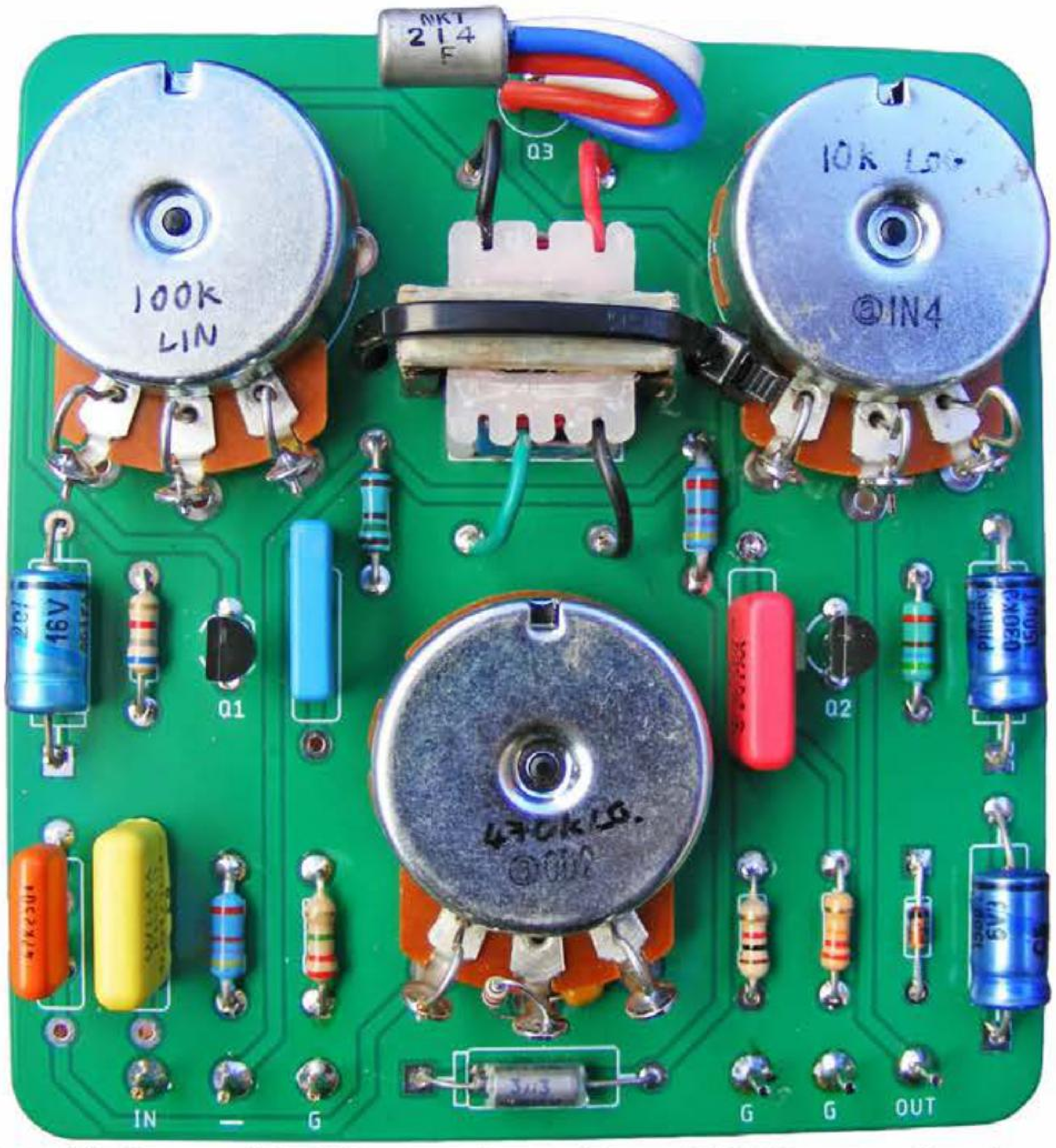


Photo 11: the completed Transmanium prototype PCB. The capacitors have been chosen because they look pretty. Any old dielectric works fine for fuzz.

transformer. It is possible to get a resonance roll-off effect in combination with the transformer's leakage inductance. Since it depends on the particular transformer used, I'll leave this for you to experiment with. With the 5:1 interstage transformer, a 22nF capacitor across the primary sounded good, getting rid of the finger clicks.

Clipping

The type of clipping is important; it should be gradual in onset, ie, soft. Symmetrical clipping is better for bass guitar, since it generates a strong third harmonic which enhances clarity, especially on loudspeaker systems with restricted bass response, where the fundamental is cutoff.

Second harmonic in isolation confuses the brain by sounding like another guitar playing an octave higher. For lead guitar, asymmetrical clipping is better, as the second harmonic enhances the screaming quality.

In most fuzz boxes, including this one, the clipping starts off asymmetric, enhanced by the square law of the JFETs. Eventually, it almost becomes a square wave when fully driven.

Of course, the tone control on the output completely changes this. In the traditional Tone Bender tone control circuit, where each end of the pot track is fed by low-pass and high-pass filters, the pot has a midrange dip in the middle, there being no flat setting. If there were, it would sound horrible. The raw clipping has to be filtered to sound good.

Flat batteries

Some guitarists have noticed that their fuzz boxes sounded better when the battery was flat. I investigated this, and mostly this was down to earlier clipping, giving more distortion. I used this effect in the Yellow Tone Bender by running the germanium transistor at a lower voltage of 4.7V rather than the normal 9V, which is what zener diode D2 is for.

I also noticed that the Tone Bender MkII sounded extra special when the battery was flat. This was due to positive feedback via the power rail, giving a peaky frequency response almost on the verge of oscillation. I did a special variant of the unit where I incorporated a 56Ω resistor in the ground line to simulate the internal resistance of a flat PP3 battery.

I told you guitar pedal electronics was crazy!

Construction

Luckily, guitar pedal construction is much more sensible, often going back to the simple kitchen tabletop techniques of the 1970s. The prototype for this design was hard-wired using tag strips, shown in Photos 9 & 10.

Appearance is a major consideration with guitar pedals. In my Colorsound work for Macari's, I'm not allowed to use surface-mount devices, and all components have to pass the visual test. When I had a batch of polyester capacitors that were moulded in grey plastic rather than the previous blue, they were rejected.

I suspect the saleslady at Rapid Electronics marked me on her computer system as nuts.

I'm considering having my fibreglass PCBs coated in a specially made brown solder resist coating to emulate the Paxolin PCBs of the 1960s. In guitar pedal electronics, the desired aesthetic is a PCB that looks like a colourful flower bed. The standard green or blue is considered undesirable.

I compromise and use the clear orange resist option provided by PCBWay and JLCPCB for my production units. I'm sorry, but the board given here will be standard green (shown in Photo 11). Fig.7 is the overlay diagram that indicates which components go where.

Mounting components

One of the trickiest parts of designing PCBs for pedals is that the controls have to be at the top of the box, rather than the side. This often necessitates pots with angled pins, as shown in Photo 12.

These usually have to be specially ordered, with high prices and high minimum order quantities. Alpha

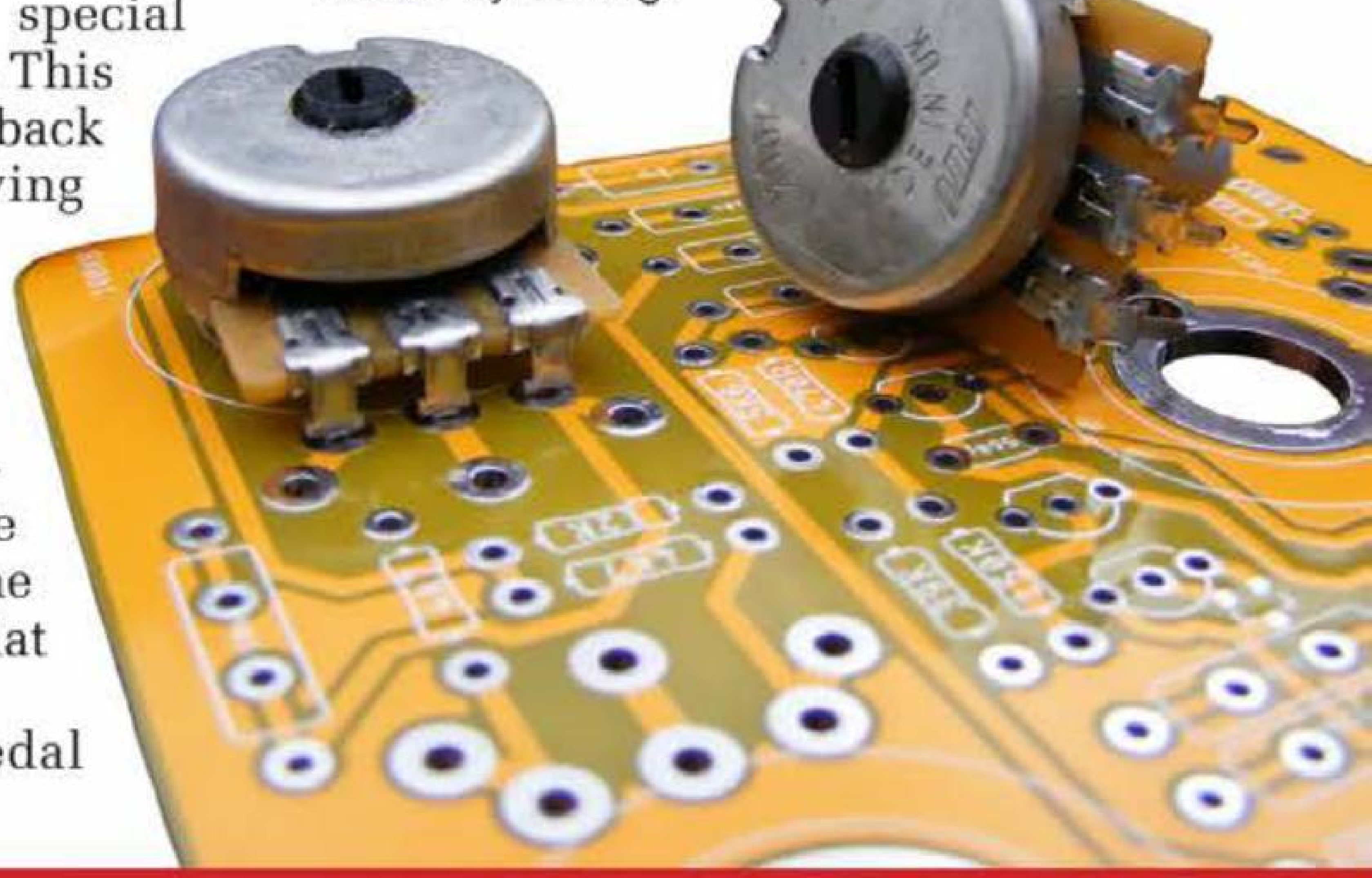


Photo 12: a pot with properly angled pins. I got them specially made by Omeg.

Photo 13: a standard tag pot with shaped lengths of 22 SWG (0.7mm diameter) tinned copper wire.

pots are normally the best value, but the MOQ for bent-pin specials is 3000.

For the Colorsound work, I use Omeg pots, which are conductive plastic and have a long life. It's still a big capital expenditure, so I have to get Macari's to pay for them. At least they can claim the VAT back. It is often necessary to use standard tag pots, so wire links have to be used from the tag to the board, as shown in Photo 13.

These are made from 35mm lengths of 0.7mm diameter enamelled copper wire, bent into a hook shape on a 3.5mm cylindrical mandrel like a 3.5mm diameter drill bit.

The pots should be mounted on the board with nuts to ensure their cases are Earthed. This means extra nuts are needed to mount the board in the box. The pot bushes need to be at least 10mm long to account for the thickness of the PCB, front panel and washers.

When the PCB is mounted up against a metal panel, it is essential to cut the component leads as short as possible to avoid short circuits. This is no problem where plated through-holes are used.

On this board, it is possible to fit standard 16mm pots (Photo 14), but they won't fully go through the holes, as shown in Photo 15.

Like small LEDs, germanium transistors are sensitive to heat and movement while soldering. It's not necessary to use a heat shunt on the leads, as has often been said in old magazine articles, but it is wise to do it quickly and use long sleeved leads (see Photo 16).

With old components, the leads are often oxidised and need plenty of scraping to ensure the solder will stick to them.

Axial capacitors

The board has dual outlines for the capacitors, so if you are into the 'retro' look, you can install pretty 1980s Philips/Mullard-style parts. Black radial electrolytics cheapen the appearance of expensive audio electronics (although there is the consideration of reliability, where modern parts most likely have the edge).

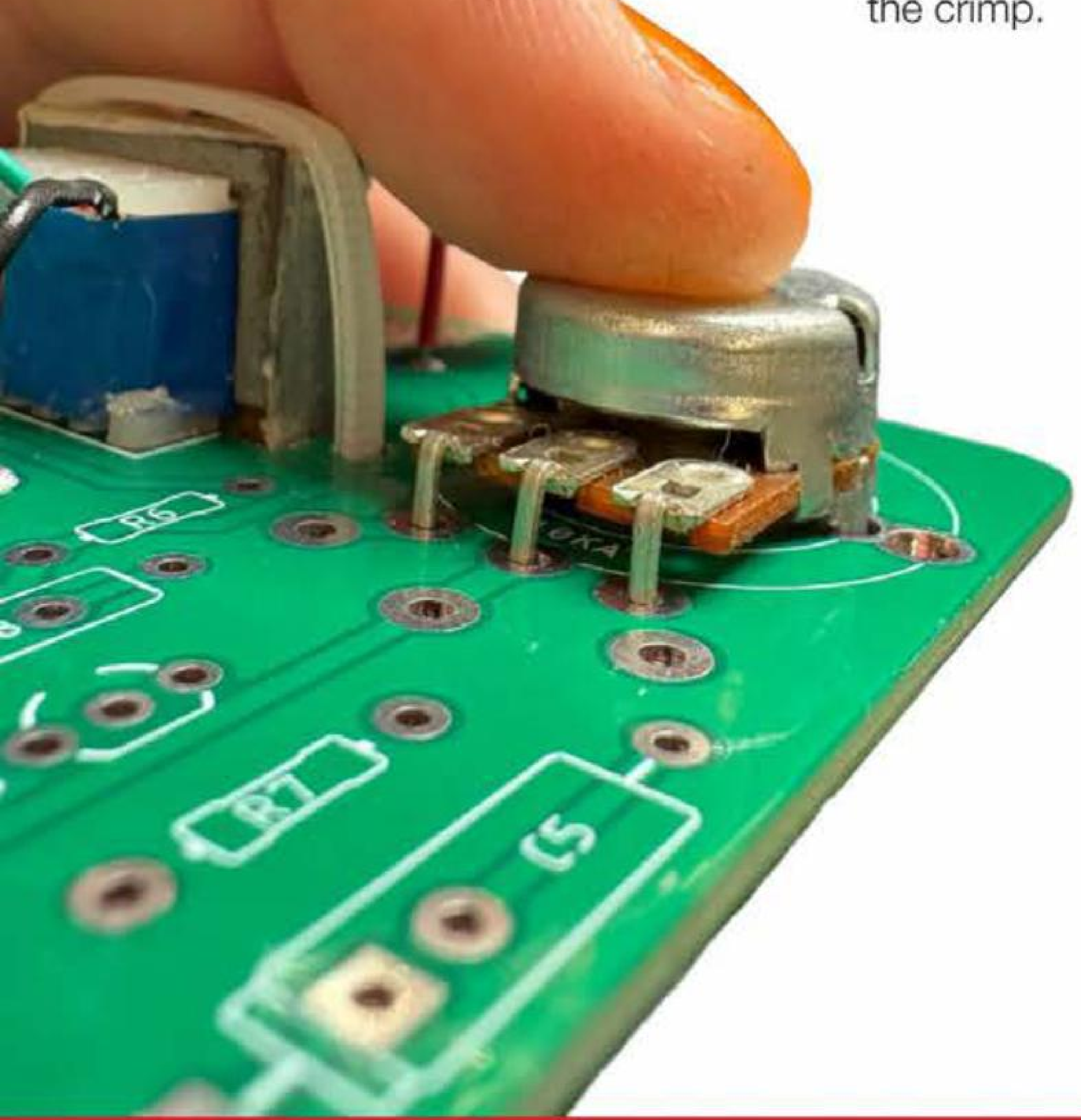


Photo 14: it is just possible to fit standard 16mm pots with a bit of judicious bending. Take care not to weaken the crimp.

Transformer

Oddly, the Greenweld interstage transformers I used had flexible lead-out wires rather than pins. There were also no mounting clamps. This made them difficult to mount. As usual, Grindle (my PCB designer friend) came up with a solution.

With modern PCB fabrication, it's easy to make any shaped hole, so the PCB has a rectangular slot to hold the transformer core, shown in Photo 17. The transformer is then clamped down with a cable tie as illustrated in Photo 18.

Testing

As usual, it's the DC conditions that are the first things to check if it doesn't work: power first, then the voltages at the transistor outputs. The voltage on TR2's drain is almost the same as the rail voltage, as is normally the case with inductor loading. That's why the output voltage swing is double compared to using a resistor.

High-frequency stability

Fuzz boxes have a very high gain, typically 40-60dB; in this case, it's 600 times or 55dB. Feedback at high frequencies from input to output, causing high-frequency oscillation, is a common problem. The input lead should be screened, and the unit enclosed in a metal box. The metal cases of the pots must also be Earthed.

If HF oscillation occurs, an added 470pF capacitor (shown dotted in Fig.6) helps. Increasing the gate stopper resistors on the JFETs can also fix it. R1 can be increased to 10kΩ, and a similar resistor could be added to TR2. These mods are shown in Photo 19.

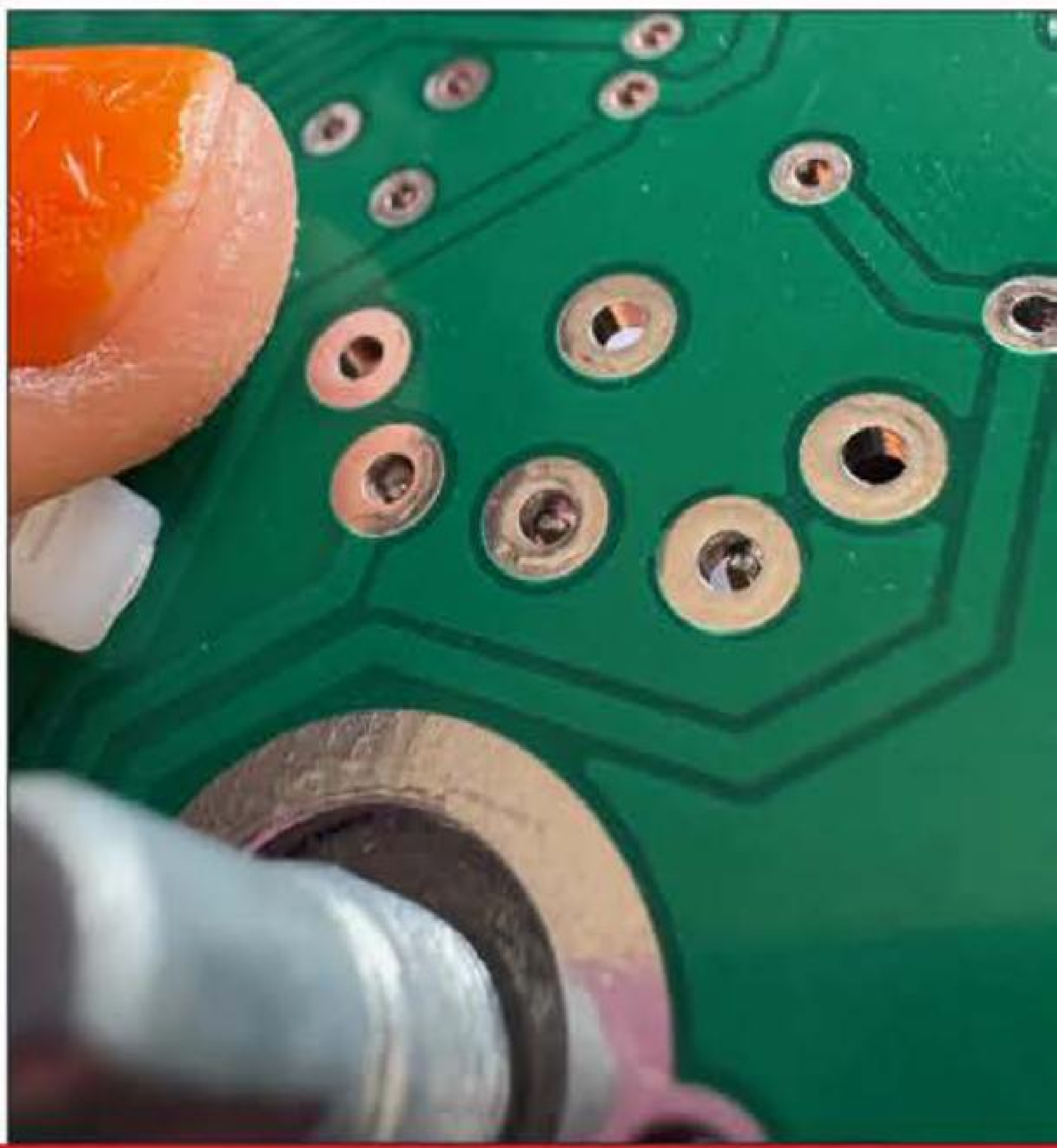
Failure modes

The simplicity of the circuits used in guitar pedals means failures are rare. I find damaged battery clips to be the number one cause. DC power connector switch contacts are second, and finally, broken pots and switches due to the guitarist's feet.

The germanium transistors can suffer internal detached emitter/collector connections and tin whisker shorts to the metal cans. Many of these problems can be traced back to the days when the production yield for these devices was very low, and the market was flooded with rejects.

I used to buy whole bags of these untested transistors from companies

Photo 15: with the 16mm pots, the tags won't quite go fully through the holes, but you can still solder them to the plated barrels.



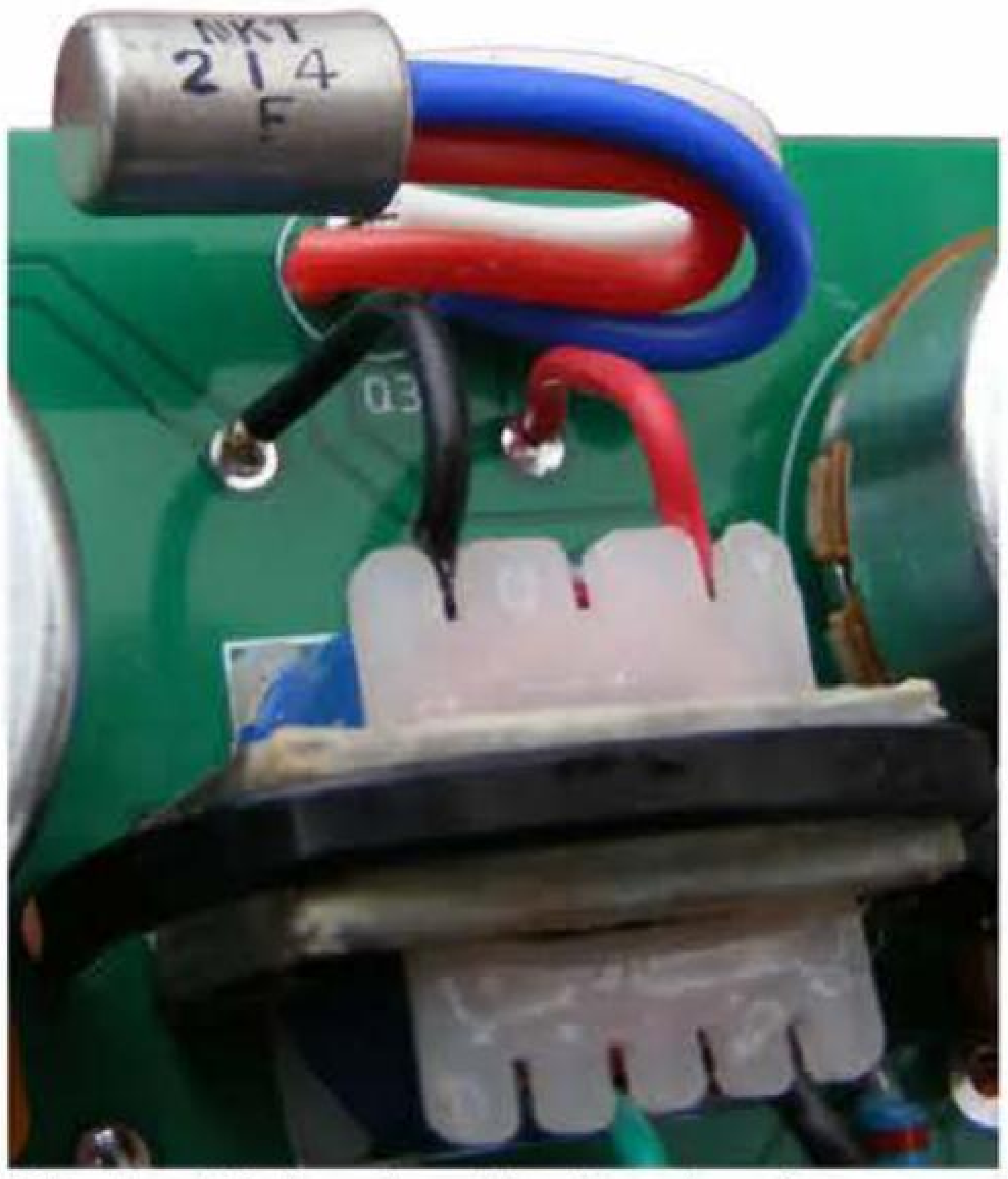


Photo 16: leaving the leads of germanium devices long prevents heat damage when soldering.

like Bi-Pak for a few quid. Many devices had no markings at all. I've used some of these defective devices to make unique musical noise and distortion generators. Sadly for today's constructors, these dud devices are now reappearing on eBay at high prices.

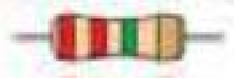
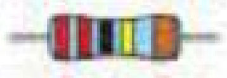
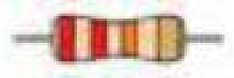
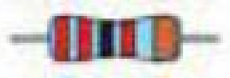
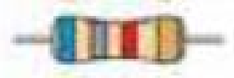
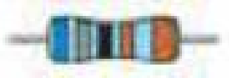
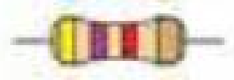
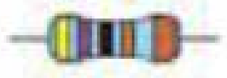
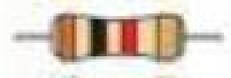
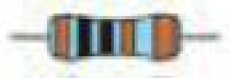
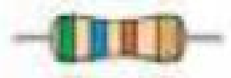
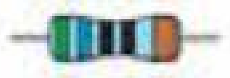
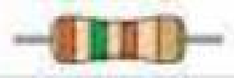
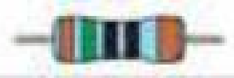
Boxing it up

I couldn't find a suitable box apart from the Colorsound ones, which are not mine. So we'll leave it for now until I find a suitable die-cast enclosure. That will be described in a future column, in which wiring up the device and suitable switching will also be covered.

If you want to learn more about fuzz boxes, check out the book "Level and Attack – the untold story of the Tone Bender fuzz" by Simon Keeping, Anthony Macari and Steve Macari (https://www.11publishing.co.uk/books/tonebender). PE

Parts List – Transmanium fuzz box

1 double-sided 85 × 80mm PCB coded AO-NOV25-01
1 Hammond or Tayda metal box
1 5:1 turns ratio interstage transformer or small transistor driver transformer, eg, LT722/LT44 (T1) **[AOShop]**
1 Tayda 3PDT latching stomp switch (S1)
2 stereo switched 6.35mm (¼-inch) chassis-mounting jack sockets (CON1, CON2)
1 PP3 battery clip (BAT1)
1 125mm-long, 2.5mm wide cable tie
3 lengths of 1mm inner diameter sleeving (for TR3)
3 extra potentiometer nuts

Qty	Value	4-band code	5-band code
1	2.2MΩ		
1	22kΩ		
1	6.8kΩ		
2	4.7kΩ		
1	1.0kΩ		
1	560Ω		
1	150Ω		

Semiconductors
1 2N5460 P-Channel JFETs (TR1, TR2)
1 NKT214F, OC71, OC81D, OC75, AC126 or similar PNP small-signal LF germanium transistor (TR3)
1 1N4148 75V 200mA signal diode (D1)

Capacitors (all can be radial or axial)
2 220µF 6.3V electrolytic (C4, C5)
1 22µF 10V electrolytic (C2)
1 3.3µF 10V electrolytic (C6)
2 47nF MKT, polyester or similar (C3, C8)
1 10nF MKT, polyester or similar (C1)
1 4.7nF MKT, polyester or similar (C7)

Potentiometers (26mm size preferred for ruggedness)
1 470kΩ-1MΩ single-gang logarithmic (VR1)
1 100kΩ single-gang linear (VR2)
1 10-22kΩ single-gang logarithmic (VR3)

Resistors (all ¼W ±10% axial or better)
1 2.2MΩ (R2)
1 22kΩ (R8)
1 6.8kΩ (R3)
2 4.7kΩ (R1, R6)
1 1kΩ (R4)
1 560Ω (R7)
1 150Ω (R5)

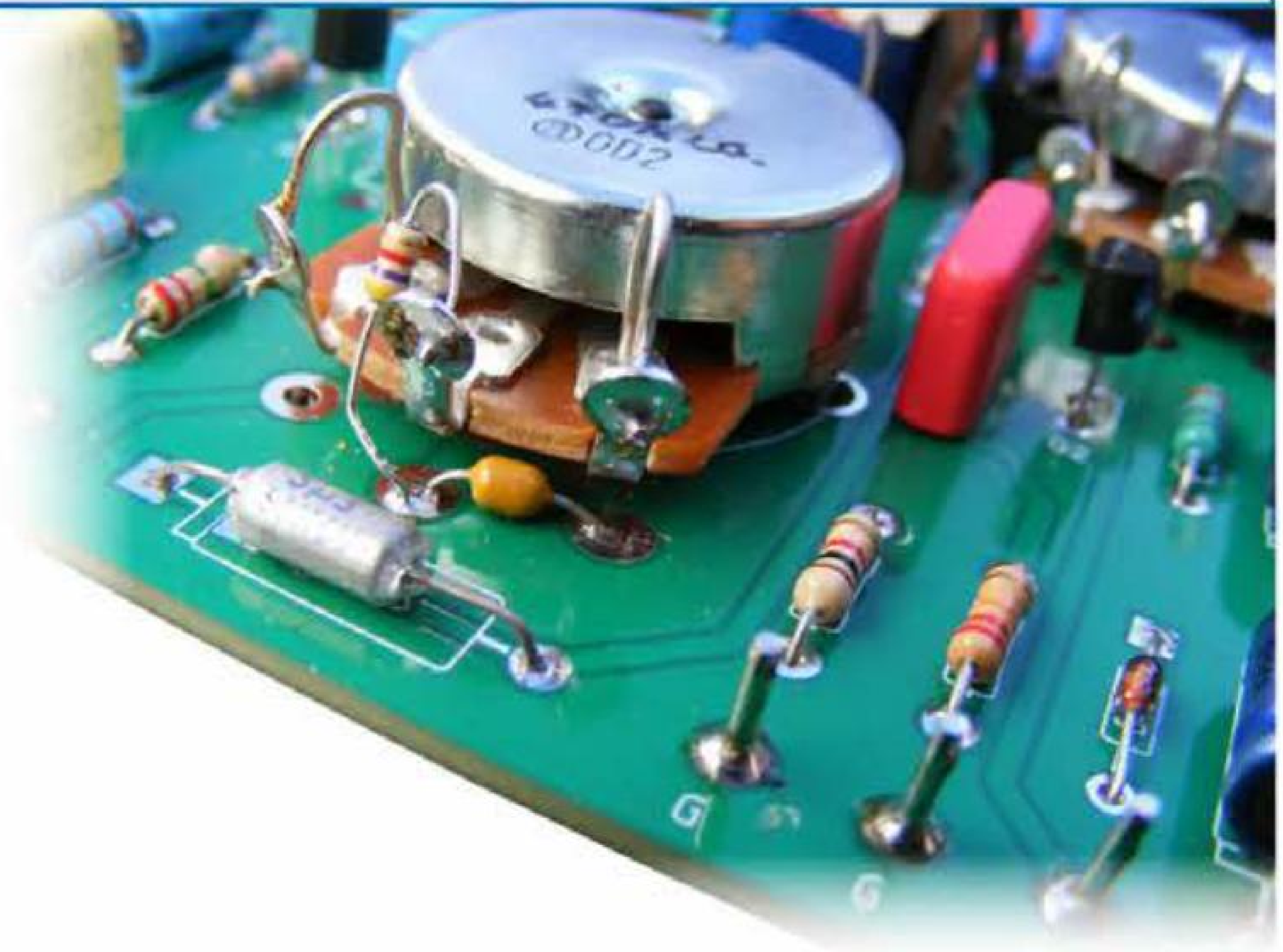


Photo 19: an extra resistor and capacitor soldered between the potentiometer tags can eliminate any high-frequency instability that may occur.

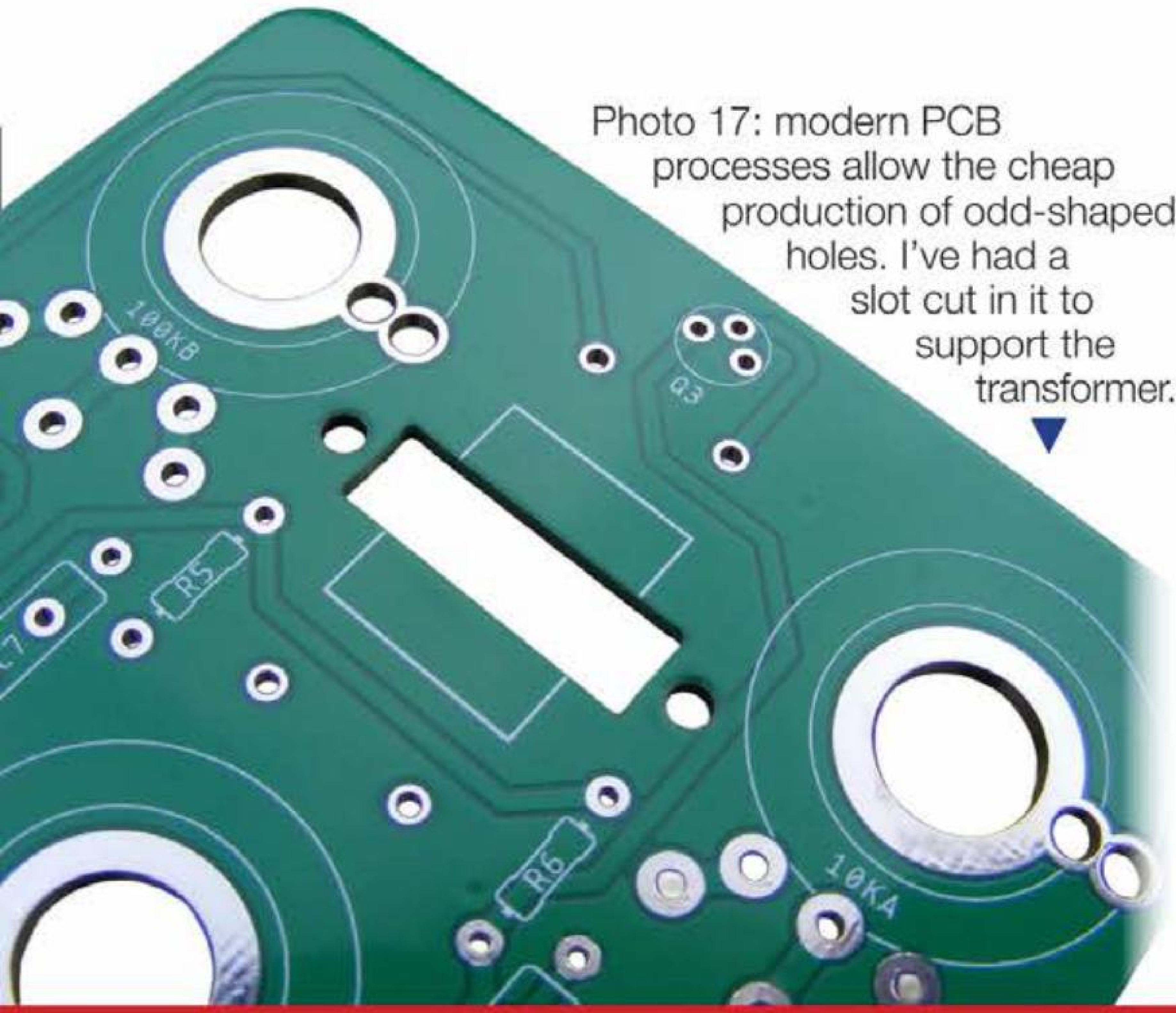


Photo 17: modern PCB processes allow the cheap production of odd-shaped holes. I've had a slot cut in it to support the transformer.

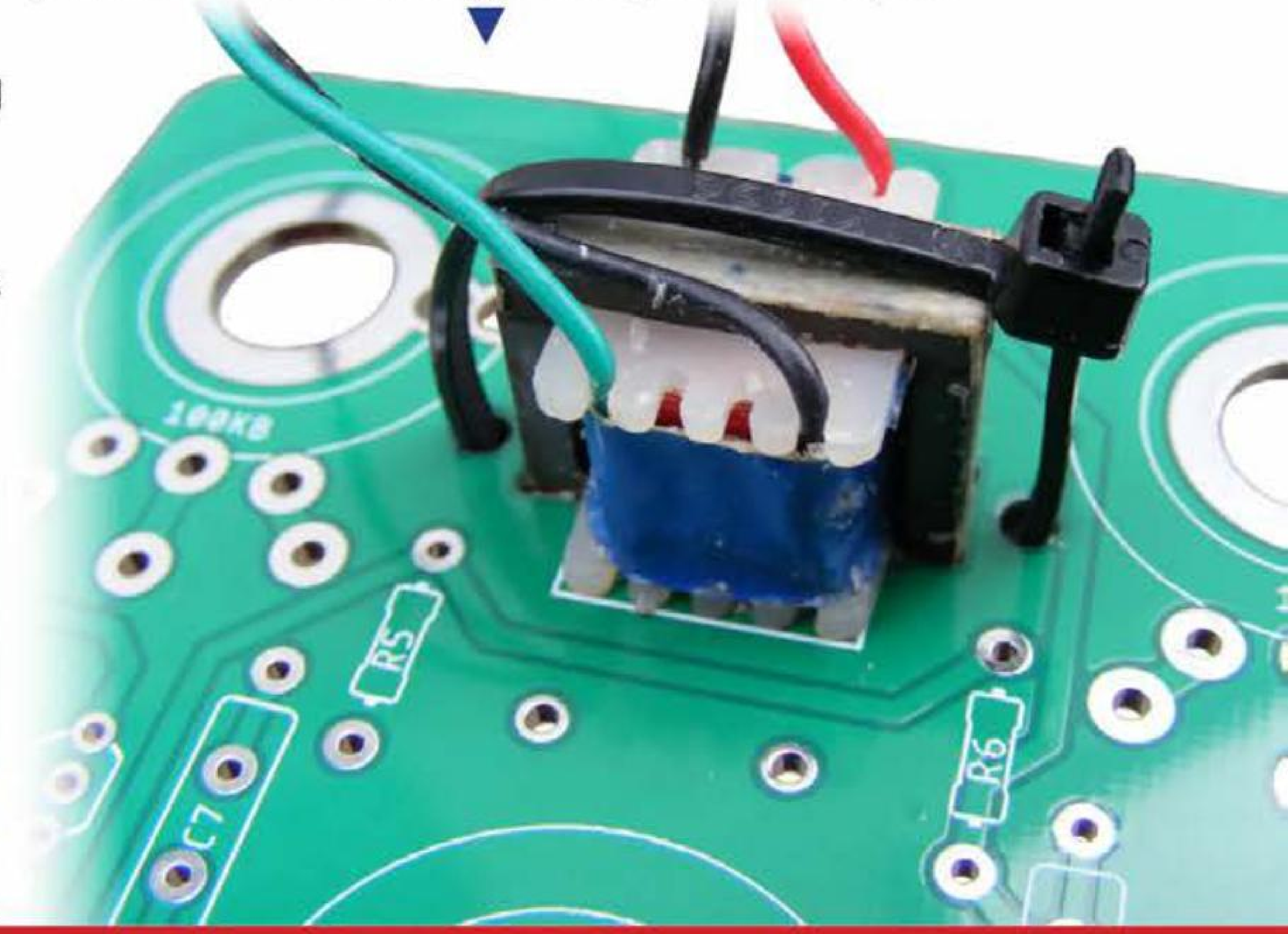


Photo 18: a cable tie is used to hold the transformer in place. It needs to be longer than you would expect.

Practical Electronics PCB SERVICE

PROJECT	CODE	PRICE
NOVEMBER 2025		
Capacitor Discharger	9047-01	£4.99
5MHz, 40A Current Probe	9049-01	£5.99
OCTOBER 2025		
Seaside Sound Simulator PCB (blue)	01111241	£7.99
Fender Jazz Bass pickguard	23109241	£5.99
J&D Luthiers T-Style pickguard	23109242	£5.99
Music Man Stingray pickguard	23109243	£5.99
Fender Telecaster pickguard	23109244	£4.99
3D Printer Filament Dryer control PCB	28110241	£4.99
SEPTEMBER 2025		
Automatic LQ Meter PCB	CSE240203A	£5.99
Automatic LQ Meter front panel (black)	CSE240204A	£5.99
Compact Hi-Fi Headphone Amplifier PCB (blue)	01103241	£4.99
Discrete Ideal Bridge Rectifier TH PCB	18108241	£2.99
Discrete Ideal Bridge Rectifier SMD PCB	18108242	£2.99
Dual Rail Supply Protector PCB	18109241	£3.99
Audio Out Cascode Amplifier PCB	CASCODEA	£4.99
Audio Out Cascode Amplifier Power Supply PCB	CASCODEP	£4.99
AUGUST 2025		
Micromite Explore-40 PCB	07106241	£2.99
Micromite Explore-40 Audio Breakout PCB	07101222	£2.99
8-Channel Learning IR Remote Receiver PCB	15108241	£5.99
FlexiDice PCB set	08107241-2	£4.99
JULY 2025		
Compact OLED Clock & Timer PCB	19101231	£4.99
180-230V DC Motor Speed Controller PCB	11104241	£9.99
Mains Power-Up Sequencer PCB (same as Feb '25)	10108231	£11.99
JUNE 2025		
Styloclone (case version)	23106241	£6.99
Styloclone (standalone version)	23106242	£7.99
Dual Mini LED Dice (TH LEDs, white solder mask)	08103241W	£2.99
Dual Mini LED Dice (TH LEDs, black solder mask)	08103241B	£2.99
Dual Mini LED Dice (SMD LEDs, white solder mask)	08103242W	£2.99
Dual Mini LED Dice (SMD LEDs, black solder mask)	08103242B	£2.99
Dual Hybrid Supply regulator board	18107211	£5.99
Dual Hybrid Supply front panel control board	18107212	£2.99
Dual Hybrid Supply CPU board	01106193	£3.99
Dual Hybrid Supply LCD adaptor	01106196	£2.99
MAY 2025		
Skill Tester 9000	08101241	£9.99
USB-C Serial Adaptor (black solder mask)	24106241	£2.99
DC Supply Protector (SMD adjustable version)	08106241	£3.99
DC Supply Protector (TH adjustable version)	08106242	£3.99
DC Supply Protector (TH fixed version)	08106243	£3.99
APRIL 2025		
ESR Test Tweezers PCB set	04105241+	£5.99
Fan Speed Controller Mk2	10104241	£4.99
Calibrated Microphone (SMD version)	01108231	£3.99
Calibrated Microphone (TH version)	01108232	£3.99
MARCH 2025		
Pico Gamer	08104241	£9.99
Compact Frequency Divider	04112231	£4.99

PROJECT	CODE	PRICE
FEBRUARY 2025		
Laser Communicator transmitter	16102241	£3.99
Laser Communicator receiver	16102242	£3.99
Model Railway Points Controller transmitter	09101241	£3.99
Model Railway Points Controller receiver	09101242	£2.99
Mains Power-Up Sequencer	10108231	£11.99
JANUARY 2025		
USB to PS/2 Converter for VGA PicoMite	07111231	£3.99
ps2x2pico USB to PS/2 Converter	07111232	£3.99
Compact Microphone Preamplifier (case version)	01110231	£5.99
Compact Microphone Preamplifier (integrated version)	01110232	£5.99
DECEMBER 2024		
Raspberry Pi Clock Radio PCB pair	19101241/2	£12.99
VGA PicoMite (blue)	07107221	£5.99
Secure Remote Switch receiver	10109231	£4.99
Secure Remote Switch transmitter (module version)	10109232	£2.99
Secure Remote Switch transmitter (discrete version)	10109233	£2.99
NOVEMBER 2024		
Ideal Diode Bridge Rectifiers (28mm square)	18101241	£3.99
Ideal Diode Bridge Rectifiers (22mm square)	18101242	£3.99
Ideal Diode Bridge Rectifiers (4-pin SIL)	18101243	£3.99
Ideal Diode Bridge Rectifiers (tiny SOT-23)	18101244	£3.99
Ideal Diode Bridge Rectifiers (standalone SMD)	18101245	£4.99
Ideal Diode Bridge Rectifiers (standalone TH; 2oz copper)	18101246	£6.99
Multi-channel Volume Control (volume PCB)	01111221	£4.99
Multi-channel Volume Control (control PCB)	01111222	£4.99
Multi-channel Volume Control (OLED PCB, black)	01111223	£4.99
OCTOBER 2024		
TQFP-32 Programming Adaptor	24108231	£4.99
TQFP-44 Programming Adaptor	24108232	£4.99
TQFP-48 Programming Adaptor	24108233	£4.99
TQFP-64 Programming Adaptor	24108234	£4.99
2m VHF FM Test Signal Generator	06107231	£4.99
SEPTEMBER 2024		
PIC Programming Adaptor	24105231	£4.99
Salad Bowl Speaker crossover	01109231	£7.99
AUGUST 2024		
Arduino ESR Meter combined L/C-ESR	04106182	£9.99
Arduino ESR Meter separate ESR	04106183	£7.99
Watering System Controller	15110231	£11.99
JULY 2024		
Dynamic NFC Tag (22 × 31mm)	06101231	£5.95
Dynamic NFC Tag (86 × 54mm)	06101232	£7.95
Reciprocal Frequency Counter	CSE230101C	£8.95
Reciprocal Frequency Counter front panel (black mask)	CSE230102	£7.95
Pi Pico-based Thermal Camera	04105231	£6.95
JUNE 2024		
Loudspeaker Test Jig	04106231	£12.95
MAY 2024		
GPS-Disciplined Oscillator	04103231	£12.95
Dual RF Amplifier	CSE220602A	£5.95
Songbird	08103231	£7.95
APRIL 2024		
Basic RF Signal Generator	CSE221001	£8.99
Basic RF Signal Generator front panel (black solder mask)	CSE220902B	£9.99
Silicon Chirp Cricket	08101231	£7.99
Test Bench 'Swiss Army Knife'	04110221	£9.99

PCBs for most recent *PE/EPE* constructional projects are available. From the July 2013 issue onwards, PCBs with eight-digit codes have silk screen overlays and, where applicable, are double-sided, have plated-through holes, and solder mask. They are similar to photos in the project articles. Earlier PCBs are likely to be more basic and may not include silk screen overlay, be single-sided, lack plated-through holes and solder mask.

Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

Magazine back issues are available – see https://www.electronpublishing.com/product-category/pe-back-issues-print-and-digital/

Double-sided | plated-through holes | solder mask

PROJECT	CODE	PRICE
MARCH 2024		
Digital Volume Control Potentiometer SMD version	01101231	£8.95
Digital Volume Control Potentiometer through-hole version	01101232	£9.95
Advanced SMD Test Tweezers body	04106221	£6.95
Advanced SMD Test Tweezers legs (pair)	04106212	£7.95
FEBRUARY 2024		
Active Mains Soft Starter	10110221	£10.95
JANUARY 2024		
Q Meter	CSE220701	£8.95
Q Meter front panel (black solder mask)	CSE220704	£7.95
Raspberry Pi Pico W BackPack	07101221	£8.95
DECEMBER 2023		
Digital Boost Regulator	24110224	£8.95
Dual-Channel Power Supply for Breadboards	04112221	£11.95
Display Adaptor for the Breadboard PSU	04112222	£9.95
NOVEMBER 2023		
LC Meter Mk3	CSE220503C	£9.95
DC Supply Filter for vehicles	08108221	£8.95
Discrete Audio Op Amp PCB	AO1-JUL23	£9.95
Discrete Audio Op Amp PCB + essential components	AO2-JUL23	£17.95
OCTOBER 2023		
Buck/Boost Charger Adaptor	14108221	£9.95
PIC Breakout Board for SOIC parts	24110225	£5.95
PIC Breakout Board for DIP parts	24110222	£5.95
AVR64DD32 Breakout board	24110223	£5.95
Automatic Train Controller	09109221	£6.95
Chuff Sound module	09109222	£6.95
SEPTEMBER 2023		
Mini LED Driver	16106221	£7.95
New GPS-Synchronised Clock	19109221	£9.95
AUGUST 2023		
110dB RF Attenuator	CSE211003	£9.95
Universal Battery Charge Controller (2023 update)	14107192	£9.95
Wide-Range OhmMeter	04109221	£12.95
JULY 2023		
Multimeter Checker/Calibrator	04107221	£10.95
JUNE 2023		
Arduino Programmable Load	04105221	£8.95
Buck-Boost LED Driver	16103221	£8.95
MAY 2023		
Precision AM-FM DDS Signal Generator	CSE211002	£14.95
Improved SMD Test Tweezers programmed PIC	0410621PIC	£12.95
AO 2x-dual-to-quad through-hole (pack of five)	AO1-MAY23	£6.95
AO 2x-dual-to-quad SMD (pack of five)	AO2-MAY23	£6.95
AO 2x-single-to-dual through-hole (pack of five)	AO3-MAY23	£6.95
AO 2x-single-to-dual SMD (pack of five)	AO4-MAY23	£6.95
APRIL 2023		
500W Amplifier Module	see p.22, April 2023	
Clipping Indicator (per channel)	01112211	£7.95
CD Welder Power Supply (one needed)	29103221	£9.95
CD Welder Controller (one needed)	29103222	£9.95
CD Welder Energy Storage module (several needed)	29103223	£7.95
AO Universal Dual Op Amp Board	AO1-APR23	£9.95
AO Stereo RIAA precision passives kit for dual op amp	AO2-APR23	£8.95

PROJECT	CODE	PRICE
MARCH 2023		
Pico BackPack	07101221	£9.95
Semaphore Signal (controller)	09103221	£7.95
Semaphore Signal (blade)	09103222	£5.95
FEBRUARY 2023		
Tesla Coil driver board	26102221	£9.95
Tesla Coil potentiometer board	26102222	£5.95
Cooling Fan Controller & Loudspeaker Protector	01102221	£8.95
Remote Gate Controller	11009121	£12.95
JANUARY 2023		
Classic LED Metronome – 8-LED	23111211	£7.95
Classic LED Metronome – 10-LED	23111212	£8.95
Multi-Channel Speaker Protector – 6 channel	01101221	£9.95
Multi-Channel Speaker Protector – 4 channel	01101222	£7.95
Remote Control Range Extender – IR-to-UHF	15109212	£5.95
Remote Control Range Extender – UHF-to-IR	15109211	£7.95
AO Universal Single Op Amp Board	AO1-JAN23	£7.95
DECEMBER 2022		
Hummingbird Amplifier	01111211	£9.95
SMD Trainer PCB	29106211A	£8.95

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NOVEMBER 2022		
USB Cable tester – main PCB	04108211	£12.95
USB Cable tester – front panel	04108212	£5.95
USB Cable tester – optional panel	SC5970	£5.95
Model Railway Carriage Lights – PCB	09109211	£6.95
AO trnsfmr PCB – standard VTX-A range	VTX-101-007	£6.95
AO trnsfmr PCB – dual-outline VTX102-3001/101-3002	VTX-Dual	£6.95
OCTOBER 2022		
SMD Test Tweezers – PCB and pair of tweezer arms	04106211-2	£11.95
SMD Test Tweezers – programmed PIC12F1572-I/SN	0410621A	£7.95
Tele-com	12110211	£12.95
SEPTEMBER 2022		
Touchscreen Digital Preamp – main board	01103191	£12.95
Touchscreen Digital Preamp – adaptor board pair	01103192	£5.95
20A DC Motor Speed Controller	11006211	£9.95
AUGUST 2022		
Multi-purpose Battery Manager – I/O Expander	11104212	£5.95
Multi-purpose Battery Manager – Switch Module	11104211	£8.95
Simple MIDI Music Keyboard (for 8 switches)	23101213	£6.95
Nano Pong	08105212	£7.95
JULY 2022		
Silicon Labs AM/FM/SW Radio	CSE210301C	£10.95
Level Crossing Controller	09108211	£6.95
JUNE 2022		
Full-wave Motor Speed Controller	1010221	£8.95
PIC Programming Helper for 8-pin PICs only	24106211	£7.95
PIC Programming Helper for 8, 14 or 20-pin PICs	24106212	£10.95
Advanced GPS Computer	05102211	£9.95
MAY 2022		
Bus board PCB for Analogue Vocoder	AO1-MAY22	£10.95
Complete set of 14 PCBs for Analogue Vocoder	AO2-MAY22	£97.95
Programmed EEPROM for Digital FX Unit	FX1-MAY22	£10.95
Programmed PIC for Digital FX Unit w/ potentiometer	FX2-MAY22	£8.95
APRIL 2022		
64-key MIDI Matrix shield	23101211	£8.95
64-key MIDI Matrix switch board	23101212	£11.95
High-current Battery Balancer	14102211	£10.95
Digital FX Unit – using potentiometer	01102211	£9.95
Digital FX Unit – using BCD switch	01102212	£9.95
Universal Audio PSU	AO1-APR22	£11.95
MARCH 2022		
Mini Isolated Serial Link	24102211	£5.95
Busy Loo Indicator	16112201	£5.95
Analogue Vocoder – Band-pass filter board	AO1-MAR22	£9.95
Analogue Vocoder – HP/LP filter board	AO2-MAR22	£9.95
FEBRUARY 2022		
Arduino-based Power Supply	18106201	£9.95
Battery Monitor Logger	11106201	£10.95
Electronic Wind Chimes	23011201	£10.95
Analogue Vocoder – Driver Amplifier	AO-FEB22	£8.95
JANUARY 2022		
Vintage battery Radio Li-ion Power Supply	11111201	£9.95
MiniHeart: A Miniature Heartbeat Simulator	01109201	£8.95
DECEMBER 2021		
AM/FM/SW Digital Receiver	CSE200902A	£13.95
Balanced Input and Attenuator for USB CODEC	01106202	£11.95

PROJECT	CODE	PRICE
NOVEMBER 2021		
Dual Battery Lifesaver	11111202	£6.95
OCTOBER 2021		
Mini Wi-Fi LCD BackPack	24106201	£8.95
SEPTEMBER 2021		
USB SuperCodec PCB	01106201	£14.95
Audio DDS Oscillator PCB	01110201	£5.95
Audio DDS Oscillator rotary encoder	01110201-ENC	6.95
Programming Adaptor Board for Audio DDS Oscillator	01110202	£5.95
High-power Ultrasonic Cleaner main PCB	04105201	£14.95
High-power Ultrasonic Cleaner front-panel PCB	04105202	
Night Keeper Lighthouse PCB	08110201	£5.95
AUGUST 2021		
Ol' Timer PCB	19104201	£11.95
Ol' Timer 8x8 RGB LED module using WS2812B	19104201-88	£8.95
Ol' Timer set of acrylic case pieces and spacer	19104201-ACR	£8.75
Ol' Timer DS3231 RTC IC wide SOIC-16	19104201-RTC	£5.95
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Published on approximately the first Thursday of each month by Silicon Chip Publications, PO Box 194 Matraville NSW 2036 Australia. Printed in England by The Manson Group, Reynolds House, 8 Porters Wood, Valley Road Industrial Estate, St Albans AL3 6PZ. Distributed by Seymour, 86 Newman St, London W1T 3EX. Subscriptions UK: £33.99 (6mo); £59.99 (12mo.); £114.99 (2yrs). EUROPE: airmail service, £38.99 (6mo); £69.99 (12mo); £129.99 (2yrs). REST OF THE WORLD: airmail service, £46.99 (6mo); £84.99 (12mo); £164.99 (2yrs). Make payments to 'Practical Electronics', Practical Electronics Subscriptions, PO Box 6337, Bournemouth BH1 9EH United Kingdom. Email: pesubs@selectps.com. PRACTICAL ELECTRONICS is sold subject to the conditions that it shall not, without the written consent of the Publishers first having been given, be lent, resold, hired out or otherwise disposed of by way of Trade at more than the recommended selling price on the cover, and that it shall not be lent, resold, hired out or otherwise disposed of in a mutilated condition or in any unauthorised cover by way of Trade or affixed to or as part of any publication or advertising, literary or pictorial matter.

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MEC2628A-UK-09-25